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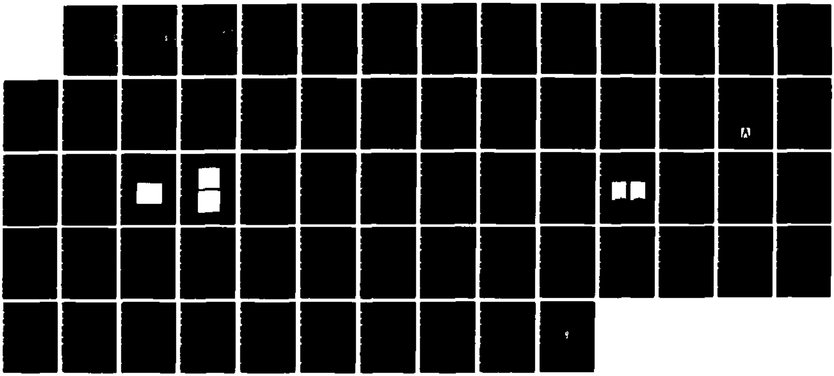

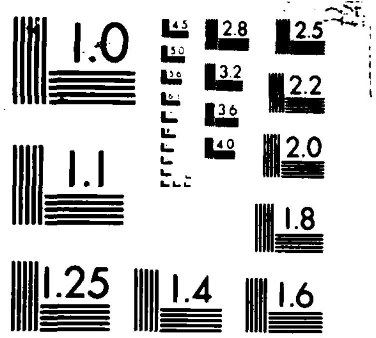

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OPTICAL PATTERN RECOGNITION USING SYNTHETIC DISCRIMINANT FUNCTIONS

THESIS

David L. Neidig
Second Lieutenant, USAF

AFIT/GE/ENG/86D-2

DEPARTMENT OF THE AIR FORCE
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Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Electrical Engineering

David L. Neidig, B.S.

Second Lieutenant, USAF

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Preface

The purpose of this thesis was to examine the effectiveness of the matched spatial filter as a pattern recognition device. The main application of this system that interests the Air Force is in a tracking scenerio. This thesis analyzes the advantages and disadvantages of the matched filter and adds a few new ideas to increase its effectiveness as a high speed tracker.

I would like to thank some of the people who made this work possible. First, I thank my thesis advisor, Major James Mills, for his insight and constant encouragement. I am also grateful to Dr. Matthew Kabrisky's guidance in the application of energy normalization. I would also like to express my gratitude to the engineers at the Avionics lab for allowing me to use their facility and equipment. I am especially grateful to Dick Lane for his practical laboratory expertise. Finally, I want to thank my parents for their support and words of encouragement.

David L. Neidig

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Abstract

This thesis analyzes the applicability of the matched spatial filter to optical pattern recognition when the object has been rotated relative to the filter. Several techniques are introduced to enhance the discrimination efficiency of the matched filter.

Energy normalization was applied to compensate for the variance in the reflected energy of targets. This allowed the matched filter to detect the desired target in the presence of bright background noise. A rotation invariant matched filter was constructed using multiple exposure holograms. Correlation averaging was also applied to make the filter rotation invariant.

Chapter I

I.1. Problem Statement

In this thesis a simple approach is used to make rotation invariant matched spatial filters. These filters were constructed by making multiple exposure holograms of the desired function. Other techniques such as energy normalization, spatial filtering, and averaging were applied to enhance the effectiveness of the matched spatial filter.

I.2. Air Force Applicability

A rotation invariant matched filter has several applications of interest to the Air Force. This system can be used to quickly analyze reconnaissance photographs. By first making a matched filter of a military target such as a missile silo, an engineer can then speed through a roll of film watching for a correlation spike. When a spike appears, that frame can be further analyzed by the human eye. This saves the intelligence officer from looking at every frame individually.

Another application is in a missile guidance system. By following the position of the correlation spike, a missile's guidance system can update its direction.

A third use is in target acquisition. An early warn-

ing satellite could make good use of a matched filter by scanning the atmosphere for incoming missiles. Every time a missile appears on the horizon, a correlation spike would reveal its location.

I.3. Background

With the advent of high performance weapons, it has become important to recognize and track military targets. The scientific community calls this task, "pattern recognition." Until 1963, pattern recognition was performed by digital computers which would compare a received image, pixel by pixel, to the image of the desired target which was stored in the computer's memory. This process is quite slow and requires an immense computer storage capability. In 1963, A. Vander Lugt published his now famous work on optical signal processing (17). His paper paved the way for research into high speed optical target detection.

I.4. Optical Pattern Recognition

The basic optical pattern recognition problem consists of three major parts: information input, processing, and output (15:721). Information input and output are fairly well established procedures, but the processing aspect introduces many problems.

The optical pattern recognition processor (shown in

Figure 1) is sometimes called a frequency plane correlator (10:1759). The input is placed in plane P_1 and can take on a variety of forms. It can be as simple as a 35mm slide or as complex as a spatial light modulator (6:149). In plane P_2 a matched spatial filter of the object to be recognized (reference object) is inserted. Plane P_3 is referred to as the correlation plane. If the input matches the reference object, a sharp spike of light will appear in P_3. If the input is similar to the reference but not exactly the same, a spike will appear, but it will not be as intense as with a perfect match. If the input is unlike the reference object, then no correlation spike will be detected in plane P_3.

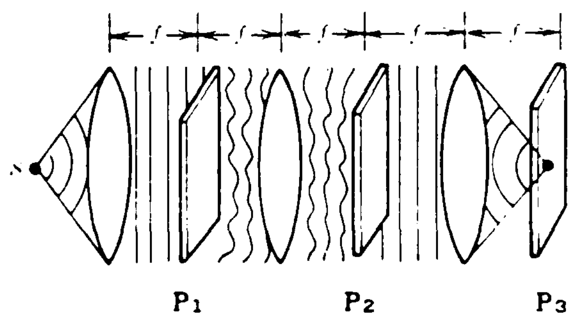


Figure 1. Optical Pattern Recognition Processor (9:179)

The applications of this process are of great importance to the Air Force. For examrle, suppose it is necessary to find a tank in an aerial reconnaissance photograph (13). First, a matched filter of the desired tank would be

made. Then, the matched filter would be placed in plane P_2 and the reconnaissance photograph in plane P_1. In plane P_3 a spike would appear at every position at which a tank was detected.

I.5. Synthetic Discriminant Functions

Although it is possible to make a matched spatial filter, there is still a very important problem that must be addressed. If the object in the scene does not have the same orientation and scale as the reference object, then the correlation will be degraded. In nearly every application of pattern recognition, the engineer is interested in finding a particular target regardless of its scale, rotation, or aspect. The example used earlier assumed that the tank in the aerial photograph had an orientation and scale identical to that of the reference. This restriction poses a very serious problem since every target can have an infinite number of views which are all slightly different from one another. Therefore, the input transparency must be compared to a host of matched filters. This situation is obviously undesirable.

In 1977, Casasent showed that the intensity of the correlation spike decreases for a rotation of only a few degrees, but there is still an appreciable output in the correlation plane (2:1654-1657). In other words, even though the target is not exactly the same as the reference,

the correlation still may be strong enough to detect the object. This fact greatly reduces the number of matched filters necessary for target identification.

In 1980, Casasent came up with the idea of recording several matched filters onto a single film plate. By choosing the views that were the most dissimilar, he was able to construct one filter with the capability of recognizing a target at many different views (10:1758-1759). Since this technique provided a method of discriminating between one target and another, it has been called a synthetic discriminant function (11:25).

I.6. Scope

In this study an iterative method was used to create a synthetic discriminant function. As unique exposures were successively added to the filter, it was observed that the discrimination capabilities were nearly increased to the point of complete discrimination. In contrast to Casasent's use of computer generated holograms, all of these filters were constructed optically.

Spatial filtering was investigated as a means of increasing the matched filter's efficiency. Both high-pass and low-pass filters were tested.

Energy normalization was also applied to increase the discrimination capabilities of the matched filter. This process was done digitally.

Finally, averages were taken for the correlation measurements as the inputs were rotated through 360 degrees. The averages were then compared to assess their discrimination capabilities.

I.7. Standards

The real test of any correlation system lies in the intensity of the correlation spike itself. Not only must the spike be very bright when a match occurs, but it must also be very dim if there is no match. Therefore, the system will be rated on its discrimination capability.

I.8. Conclusion

The goal of this project was to make the optical pattern recognition process more efficient. By using energy normalization, correlation averaging, and synthetic discriminant functions, the correlation capabilities of the matched spatial filter were enhanced. These techniques may prove to be crucial in making the matched filter a feasible component for the Air Force.

Chapter II

II.1. Matched Filters

Until 1963 no practical system for optically recognizing targets had been developed. That year A. Vander Lugt proposed a method that has become the standard for many optical processing systems (17:139). This method was also the basis for this thesis.

The basic theory behind optical pattern recognition can be found in many sources (9)(12)(19). A brief review will be included here for completeness.

A simplified optical processor is shown in Figure 2. A coherent light source, S, is collimated by lens L_1. This produces a plane wave at plane P_1 where the input ($g(x_1,y_1)$) to the system will be placed. Lens L_2 takes the Fourier transform of the input producing $G(x_2,y_2)$ at plane I_2. A mask of transmittance $H(x_2,y_2)$ is placed in plane P_2. Thus, immediately after plane P_2 the wave can be described as the product of G and H. Lens L_3 takes the transform of this product and produces the function $F\{GH\}$ in plane P_3. ($F\{\}$ designates a Fourier transform.)

From Fourier transform theory it can be shown that a correlation between two functions, g and h, can be found by taking the Fourier transform of the product GH^* where $G=F\{g\}$ and $H=F\{h\}$ (9:10). Relating this back to Figure 2,

it can be seen that by creating a mask of intensity H* and inserting it into plane P_2, the optical processor is in fact finding the correlation between the input, g, and a reference function, h. If the input function is identical to the reference function (i.e. g=h), then the output will be the auto-correlation, and an intense spike will appear in plane P_3. If the input is not identical to the reference funtion, then the output will be the cross-correlation, and the intensity of the spike in plane P_3 will depend upon how similar the input is to the reference. (i.e. The higher the similarity, the greater the intensity.)

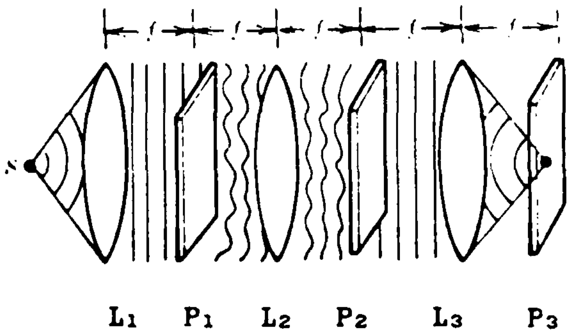


Figure 2. Basic Optical Processor (9:179)

Using an interferometric system, Vander Lugt developed a method of making a mask of transmittance H* (18). In Figure 3 the reference function, h, is placed in plane P_1. Lens L_2 produces a scaled version of the Fourier transfrom of h in plane P_2. This scaled transform is interfered with a plane wave, and the resulting intensity distribution is

recorded onto a film plate placed in plane P_3. The intensity distribution incident upon the plate is therefore

$$\mathcal{I}(x_2,y_2) = \left| r_0 \exp(-j2\pi\alpha y_2) + \frac{1}{\lambda f} H\left[\frac{x_2}{\lambda f},\frac{y_2}{\lambda f}\right]\right|^2$$

$$= r_0^2 + \frac{1}{\lambda^2 f^2}\left|H\left[\frac{x_2}{\lambda f},\frac{y_2}{\lambda f}\right]\right|^2 + \frac{r_0}{\lambda f} H\left[\frac{x_2}{\lambda f},\frac{y_2}{\lambda f}\right]\exp(j2\pi\alpha y_2)$$

$$+ \frac{r_0}{\lambda f} H^*\left[\frac{x_2}{\lambda f},\frac{y_2}{\lambda f}\right]\exp(-j2\pi\alpha y_2) \quad (1)$$

where $\alpha = \frac{\sin\theta}{\lambda}$ and r_0 is the amplitude of the plane wave.

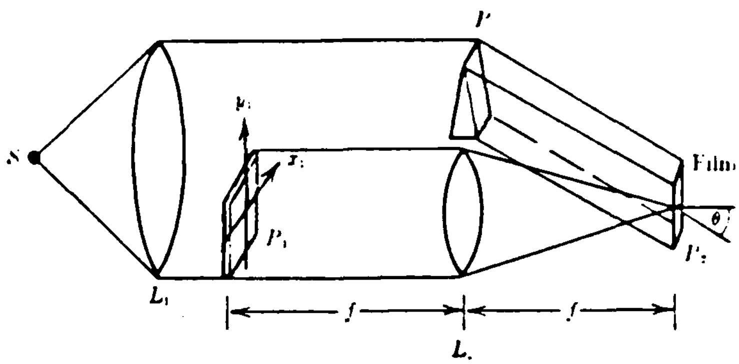


Figure 3. Vander Lugt Filter Generation (9:172)

Finally, the film is developed to produce a transmittance proportional to the intensity incident during exposure. Therefore, the transmittance of the mask is

$$T(x_2,y_2) \propto r_0^2 + \frac{1}{\lambda^2 f^2}|H|^2 + \frac{r_0}{\lambda f} H \exp(j2\pi\alpha y_2)$$

$$+ \frac{r_0}{\lambda f} H^* \exp(-j2\pi\alpha y_2) \quad (2)$$

This mask is in turn placed into plane P_2 of the optical processor (Figure 2). The field just behind the mask, when g is in the input plane, is then

$$U_2 \propto \frac{r_0^2 G}{\lambda f} + \frac{1}{\lambda^3 f^3} |H|^2 G + \frac{r_0}{\lambda^2 f^2} HG \exp(j2\pi\alpha y_2) + \frac{r_0}{\lambda^2 f^2} H^* G \exp(-j2\pi\alpha y_2) \tag{3}$$

Lens L_3 takes the Fourier transform of this field and produces the proportionality

$$\begin{aligned} U_3(x_3,y_3) \propto\ & r_0^2 g(x_3,y_3) + \frac{1}{\lambda^2 f^2}[h(x_3,y_3) * h^*(-x_3,-y_3) * g(x_3,y_3)] \\ & + \frac{r_0}{\lambda f}[h(x_3,y_3) * g(x_3,y_3) * \delta(x_3,y_3+\alpha\lambda f)] \\ & + \frac{r_0}{\lambda f}[h^*(-x_3,-y_3) * g(x_3,y_3) * \delta(x_3,y_3-\alpha\lambda f)] \end{aligned} \tag{4}$$

in plane P_3. The fourth term of this equation is simply the cross-correlation of g and h centered at a position $(0,\alpha\lambda f)$. The other terms of Equation (4) are not of interest here. Care must be taken when constructing the filter to assure that the extraneous portions of the output do not overlap with the correlation (9:175).

II.2. Correlation Degradation

As stated earlier, when the input function matches the

reference function, a sharp spike will appear in the correlation plane. Unfortunately, several factors can degrade the correlation spike and must be considered when using this method of pattern recognition.

The first problem occurs in the generation of the matched filter itself. Equation (2) gives the amplitude transmittance of the filter, and Appendix A describes how this function is recorded onto the film. From this description it can be seen that the exposure level must be set very carefully to ensure operation in the linear region of the film. Since the intensity of the Fourier transform incident on the film during construction of the matched filter is not a constant, r_o (beam ratio) must be set so that the interference between the plane waves and the proper harmonics is recorded in the linear region. For a further discussion on this topic see reference (3).

A second problem arises in the positioning of the matched filter in the optical processor (Figure 2). As the filter is misaligned from the focal plane of lens L_2 in a direction parallel to the optical axis, a slight loss of correlation occurs. The biggest problem with this misalignment is that the correlation becomes space variant. In other words, if the input is shifted from one position to another in plane P_1, the correlation changes. This makes the system useless for detecting multiple targets since each one will give a different correlation intensity.

If the filter remains in the focal plane but is

misaligned laterally, the results are more dramatic. The correlation spike may be degraded by severals decibels for a lateral shift of only a few microns (18:1222). The amount of degradation depends upon the scale of the filter. Therefore, by increasing the size of the Fourier transform in the matched filter construction, the effects of a fixed lateral displacement can be reduced.

Other sources of correlation degradation lie in differences between the input and the reference function. The first problem occurs with a difference of scale. According to work done by Casasent and Furman, a 10 dB loss occurs for a scale difference of only 1% (2:1652).

Another source of error can be categorized as rotational degradation. When the input is a rotated version of the reference, the correlation drops off significantly (2:1654). Results of rotational degradation experiments are given in Chapter III.

II.3. Energy Normalization

From equation 4 it is seen that the last term is the correlation of g and h ($g \circledast h$). Taking the one-dimensional case for simplicity, the input function can be re-written as

$$g = ag(x) \tag{5}$$

where a is a constant. The correlation term can then be

written as $a[g(x) \circledast h(x)]$. From this it is obvious that the amplitude of the correlation is directly proportional to the amplitude of the input. As the value of a is increased, the correlation gets stronger. Thus, given two functions, $g_1=ag(x)$ and $g_2=bg(x)$, with a>b, the function g_1 will provide a greater correlation spike. The constants, a and b, are analogous to the energy passing through the input plane P_1.

This can be related back to the problem of finding a tank in an aerial reconnaisance photograph (section I.3.). For instance, a bright truck may correlate better than a dull tank simply because the truck reflects more energy.

This problem has been solved in digital pattern recognition by a technique called energy normalization (16:103). The energy in an image is defined to be the summation of the squares of the intensity of each pixel.

$$\text{Energy}= \sum_i \sum_j I^2(i,j) \qquad (6)$$

where I(i,j) is the intensity of the pixel at a point (i,j) (14:41). The correlation intensity is then divided by this value to produce an energy normalized correlation.

Energy normalization can also be applied to an optical system. By placing a beam splitter after plane P_1 and sampling the energy passing through the input function (Figure 4), the input intensity can be measured. The correlation intensity is then divided by the incident energy.

The output of the processor system then is:

$$\text{Output} = \frac{g \circledast h}{\text{incident energy}} = \frac{a g_n(x) \circledast h(x)}{a} = g_n(x) \circledast h(x) \qquad (7)$$

The effects of this operation are shown in section III.2.

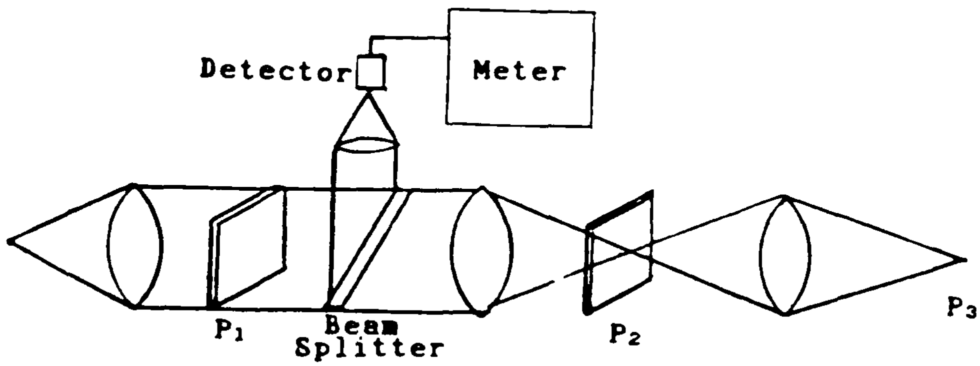


Figure 4. Energy Normalized Optical Processor

II.4. Discrimination

The basic goal of the optical pattern recognition system is to give a high correlation for the correct input and a low correlation for all other inputs. In other words, the system must be able to discriminate between the desired target and all other targets. For the example of the tank in the aerial photograph, the system must provide a correlation spike for all views of the tank that is greater than the correlation for any view of any other object.

Two different types of discrimination are possible. Intra-class pattern recognition is the ability to recognize a target regardless of its geometry (rotation, aspect, or scale). Inter-class recognition is the ability to dis-

criminate between targets without any geometrical distortions (i.e. finding tanks and not finding trucks) (11:25) (4:136). Thus, a practical system must be a combination of intra-class and inter-class discrimination.

The reference function, can be thought of as a summation of individual views (aspects or rotations).

$$h = \sum_{i=1}^{\infty} h_i \tag{8}$$

where h_i is an individual aspect or rotation of the reference function h.

A synthetic discriminant function, h', is a subset of the function, h, chosen such that

$$h' \circledast h \simeq h \circledast h \tag{9}$$

Let g_n be the set of objects to be input into the system. The goal is to develop a function, h', such that

$$g_1 \circledast h' > g_2 \circledast h' \tag{10}$$

where g_1 is any element of the reference function, h, and g_2 is any non-member of h. Several algorithms have been developed to generate the function h' to achieve this goal (4)(10)(15). In Chapter III it is shown that by successively adding elements of h to h', nearly complete discrimination can be achieved.

Chapter III

III.1. Experimental Configuration

All of the experimental work was completed using the same optical processor. The basic design is similar to that used in Figure 3, but it was modified slightly to add the necessary experimental flexibility.

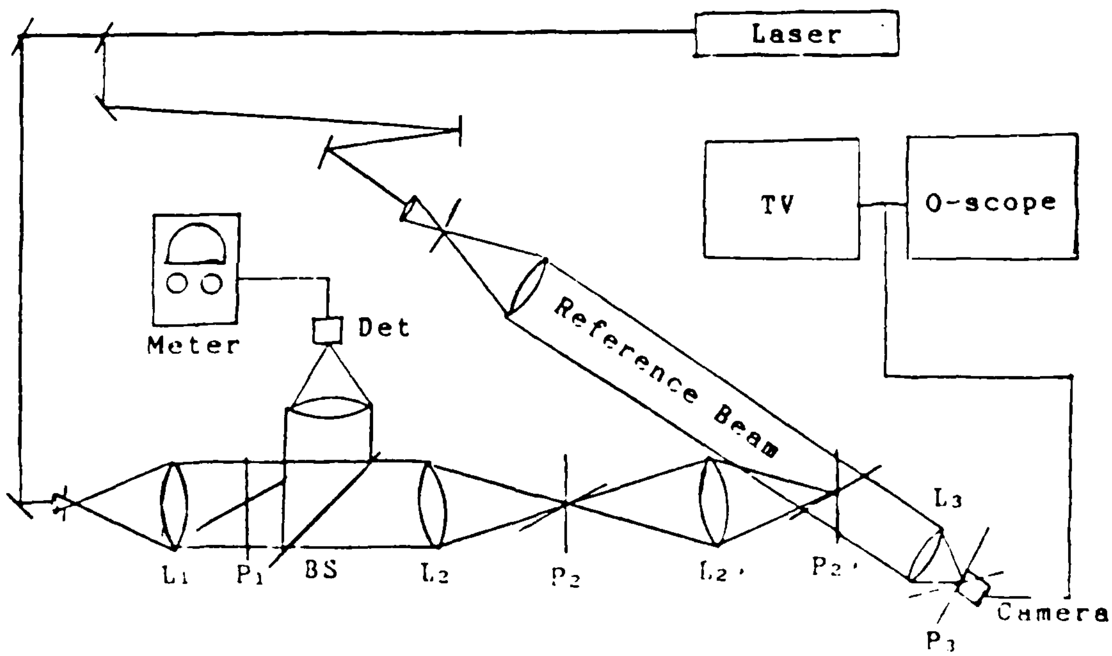


Figure 5. Experimental Configuration

Figure 5 shows the basic set-up used throughout the experiments. The input in plane P_1 was a 35mm slide of the letters of the alphabet. A mask was placed over the slide so that one letter could be used at a time. A beam splitter (BS) was placed immediately after the input plane, P_1.

The reflected portion of the beam was measured and used for energy normalization.

The Fourier transform of the input appeared in plane P_2. When high-pass and low-pass spatial filters were used, they were placed in this plane. The transform was then imaged onto plane P_2' where the matched filter was constructed by interfering the transform with the reference wave. After developing, the matched filter was returned to plane P_2' for testing.

Correlation measurements were made in plane P_3. A TV camera was placed in this plane. The output from the camera was fed to a TV and to an oscilloscope. The TV was used to observe the shape of the correlation spike while the oscilloscope gave the intensity measurements.

III.2. Regular Matched Filter

The first experiment consisted of making a simple Vander Lugt filter. The input was a binary "A" (transparent letter with an opaque background as in Figure 6).

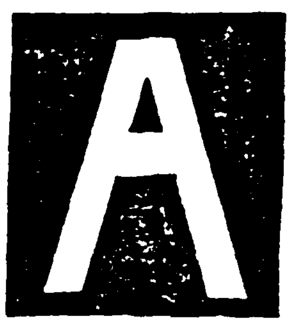


Figure 6. Vander Lugt Filter Input

The filter was constructed by interfering the reference beam (uniform plane wave) with the Fourier transform of the letter. Then, the filter was developed using the process outlined in Appendix B.

The filter was then tested against a binary representation of unrotated versions of each letter of the alphabet. Figure 7 shows the actual correlation peaks measured on the oscilloscope. Figure 8 shows these same peaks after energy normalization.

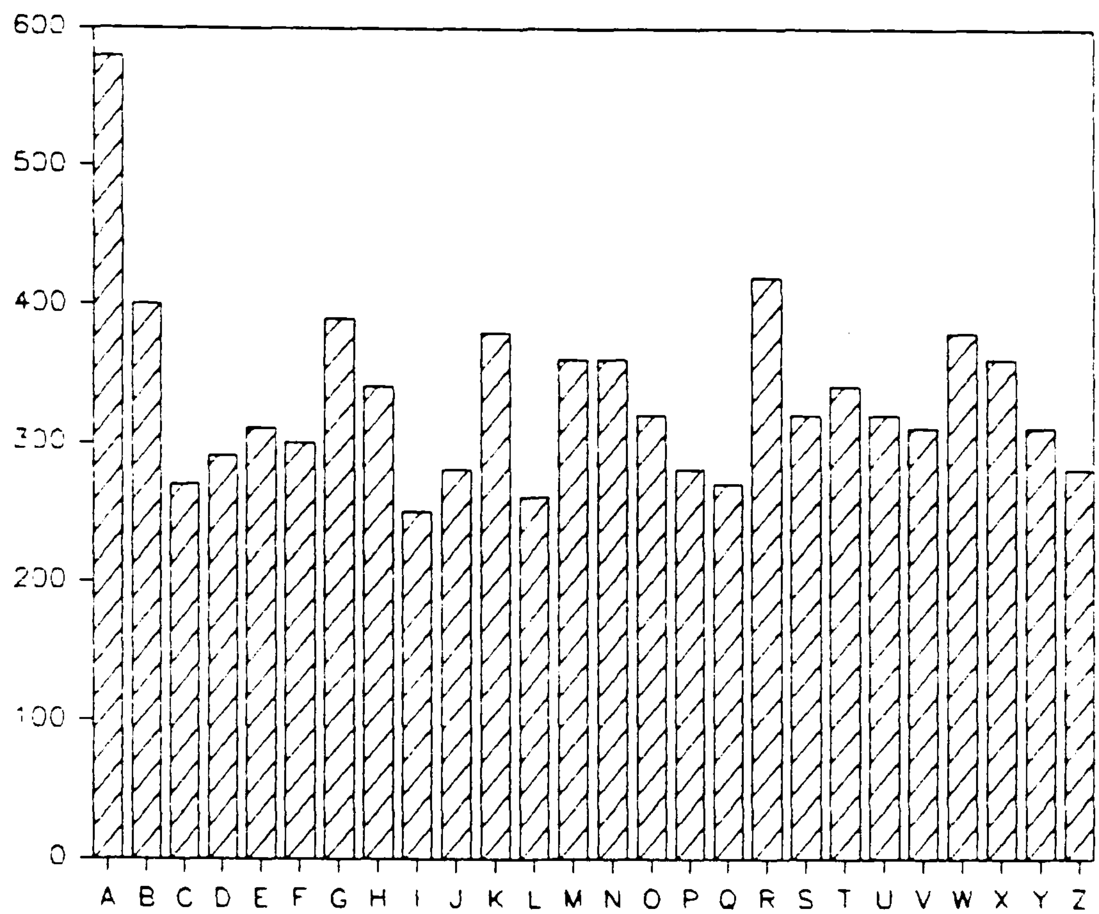


Figure 7. Correlation Peaks

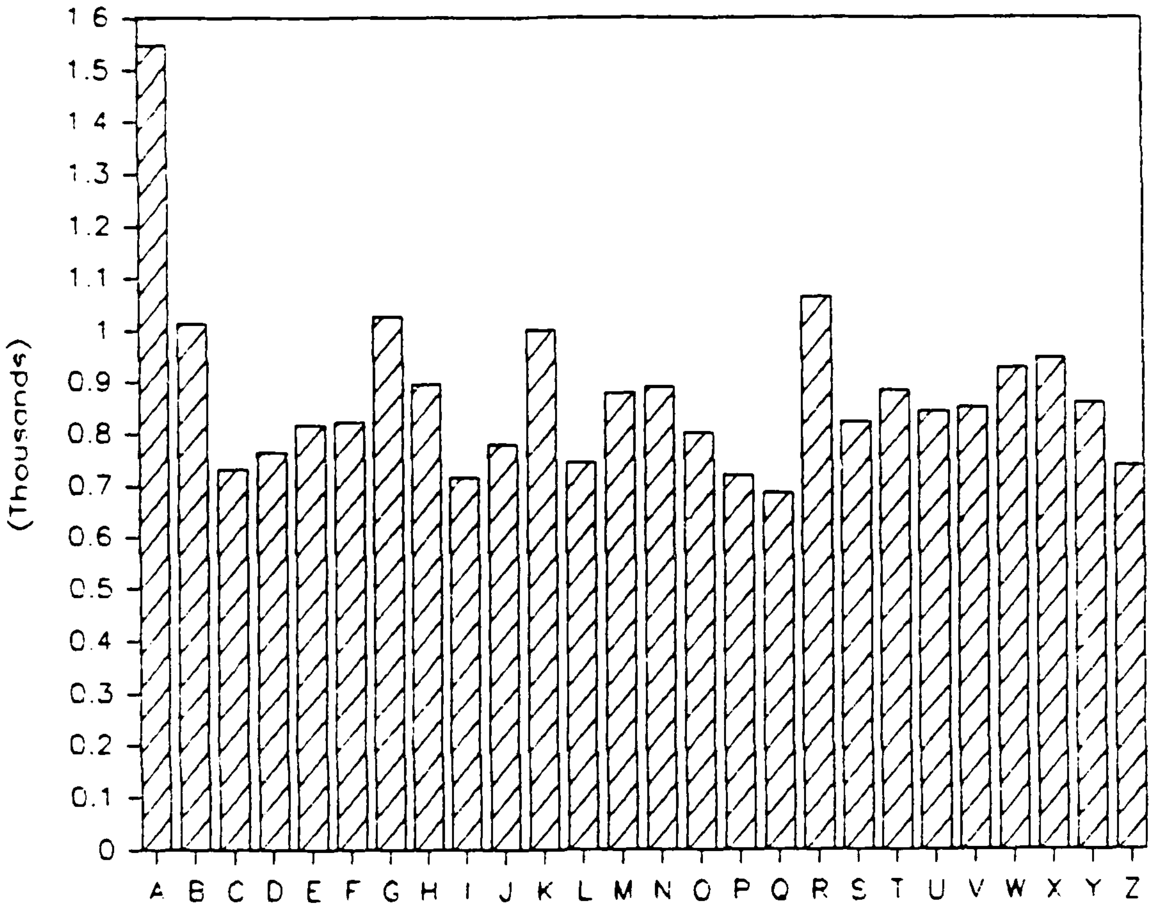


Figure 8. Energy Normalized Correlation Peaks

III.3. Rotational Variations

Up to this point no consideration has been given to geometric distortions (scale, rotation, or aspect). As an example of the effects of geometric distortions, the normalized correlation of several letters was measured as a function of rotation. Figure 9 shows the results of the normalized cross-correlation between the reference letter

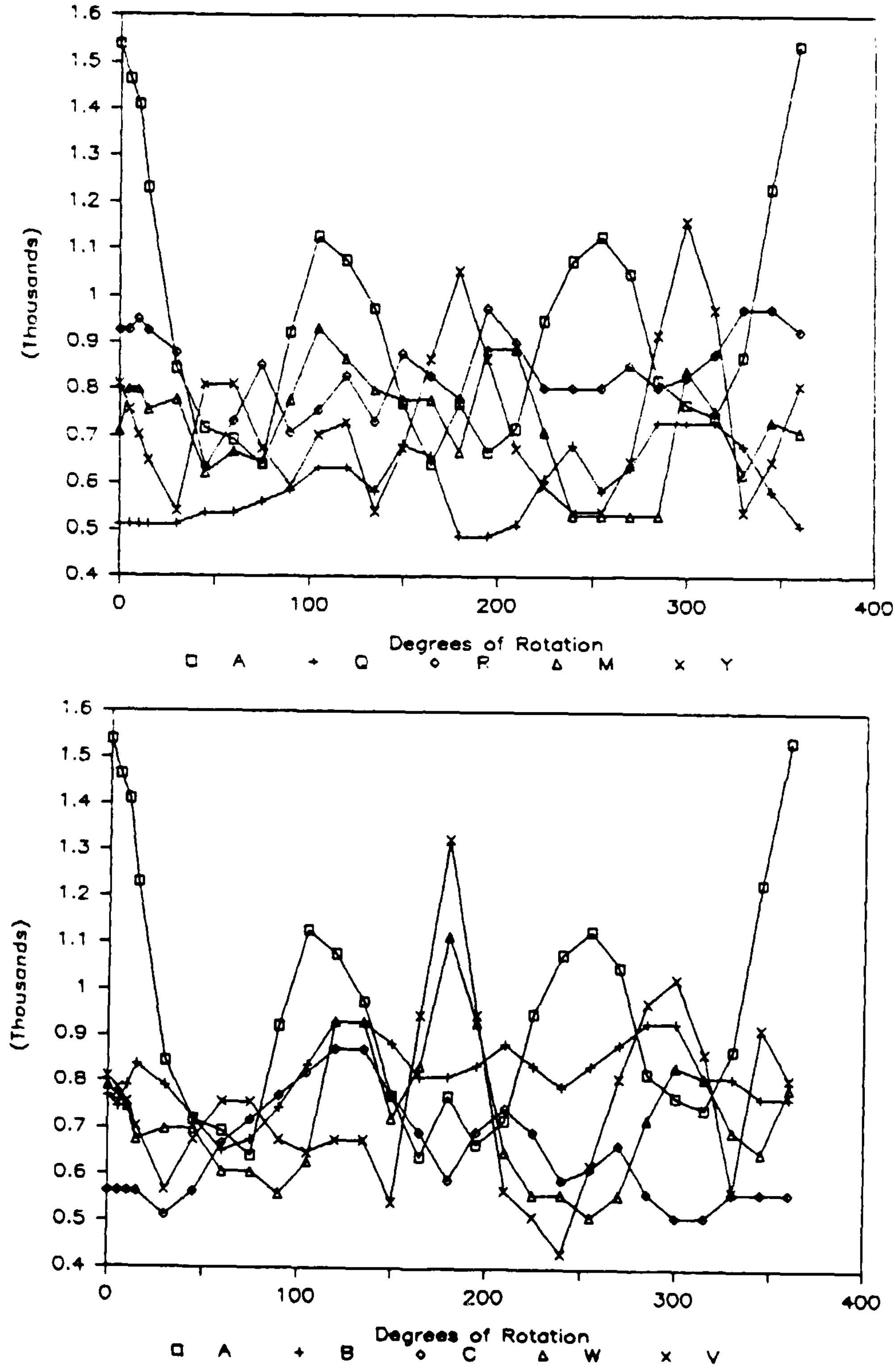


Figure 9. Normalized Correlation of "A" with Several Other Letters vs. Input Rotation Angle

"A" and the rotated versions of several letters. The correlation is plotted as a function of rotation.

Several important details should be noted on these graphs. First, notice how quickly the correlation of the letter "A" drops off as the letter is rotated. Also note how the correlation with the "A" rises again at approximately 120° and 240°. By observing the actual Fourier transform of an "A" in Figure 10, it can be seen that at rotations of 120° and 240° the input produces a transform that is similar to that of the reference function.

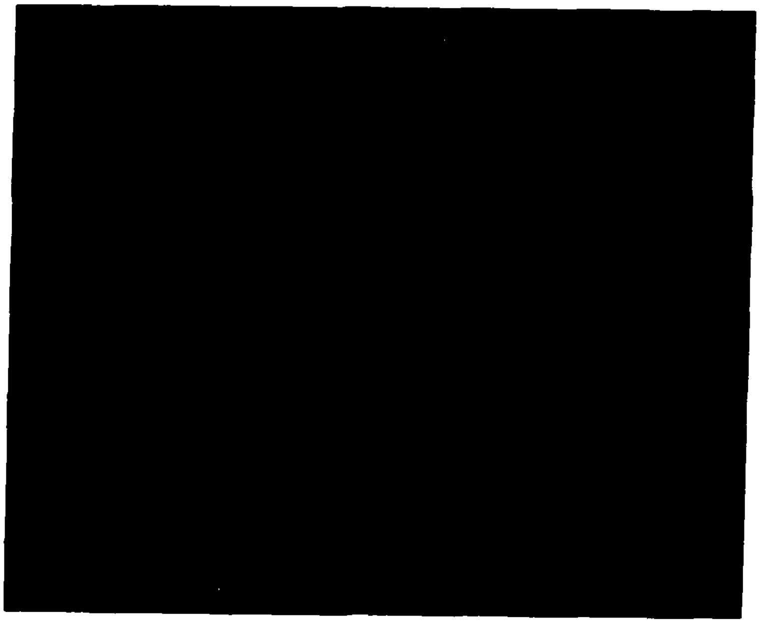


Figure 10. Fourier Transform of "A"

Secondly notice how rotated versions of several letters have rather high correlation peaks, but they do not reach the intensity of the auto-correlation. Once again by observing the similarity in the structure of the Fourier

transforms of the "V" and "W" (Figures 11 and 12) to that of the "A", the reason for the high correlation becomes apparent.

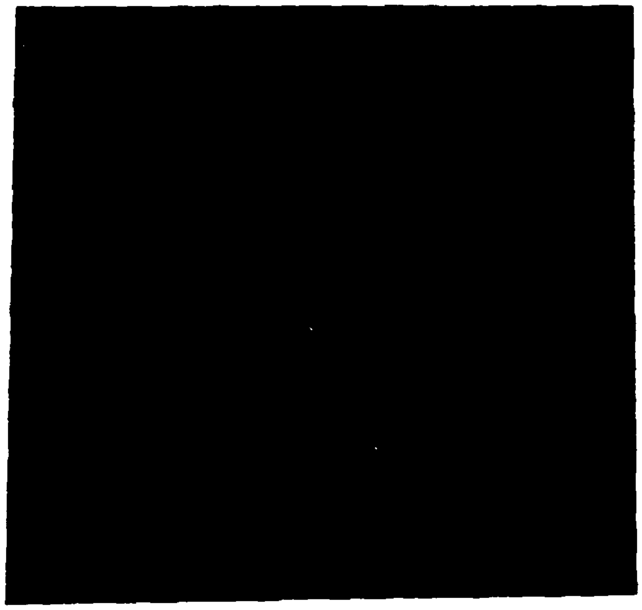


Figure 11. Fourier Transform of "V"

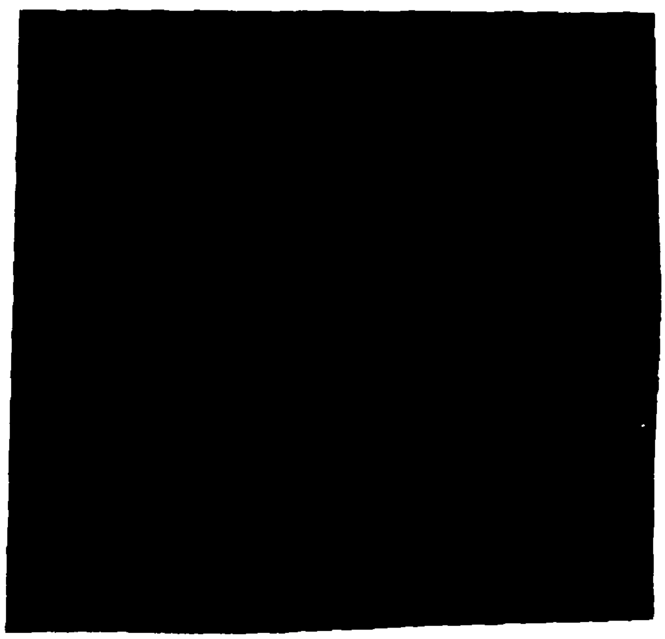


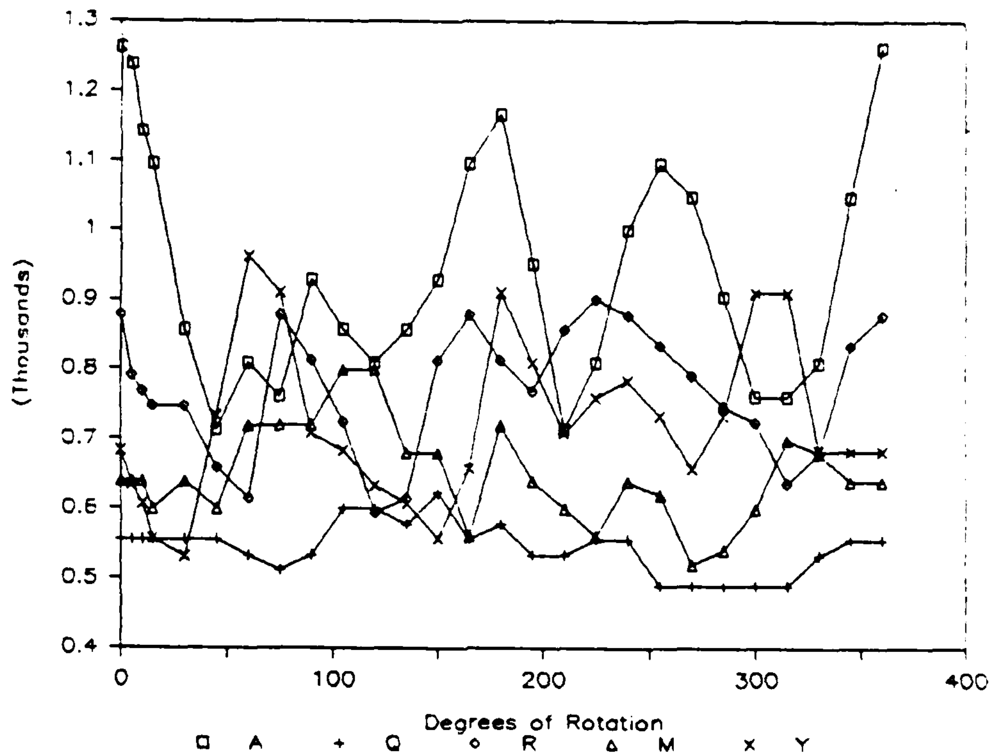
Figure 12. Fourier Transform of "W"

Although some letters have very high correlation peaks, they never quite reach the level attained by the auto-correlation of the input. Thus, we can say that the Vander Lugt filter provides good inter-class discrimination but fails to offer intra-class recognition.

III.4. Multiple Exposure Filters

The next experiment involved the construction of filters with intra-class recognition capabilities. Once again, the letter "A" was used as an input in the configuration of Figure 5. The correlation plot of Figure 9 was used as a starting point to determine the exposures to be used in subsequent filters.

A new filter was constructed with two exposures. First, the input was placed in its normal position, and the photographic plate in plane P_2, was exposed. Then, the input was rotated 180°, and the plate was exposed a second time. (180° was chosen by observing that the correlation of the "A" in Figure 9 reached a low value at that rotation.) The total exposure time of this new filter approximately equalled that of filter #1 thus keeping the exposure within the linear region of the H-D curve (Appendix A). The correlation plot of this new filter (filter #2) is shown in Figure 13. Notice how filter #2 has a much better intra-class recognition than filter #1. (i.e. More rotations are recognized.) By adding different rotations to



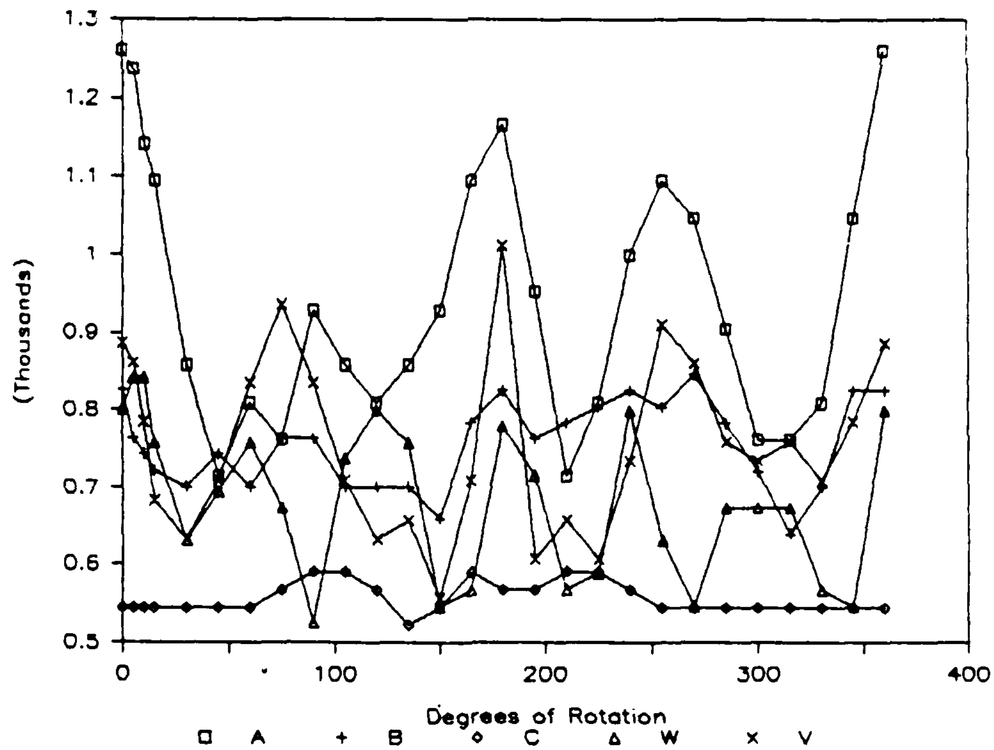
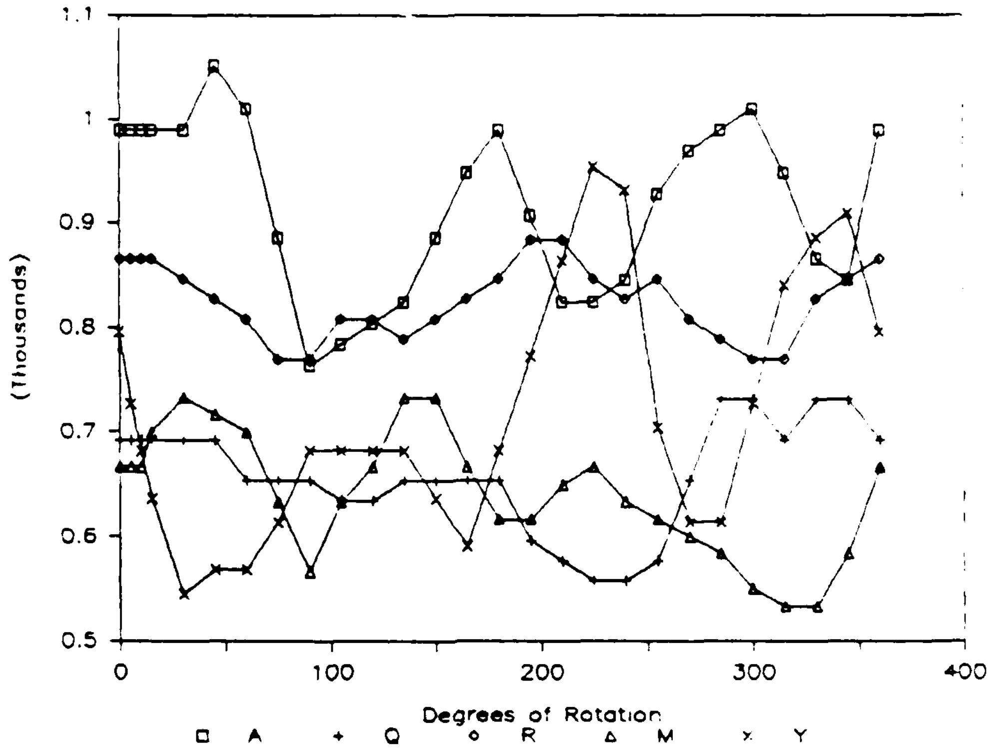


Figure 13. Correlation of 2 Exposure Filter (#2)



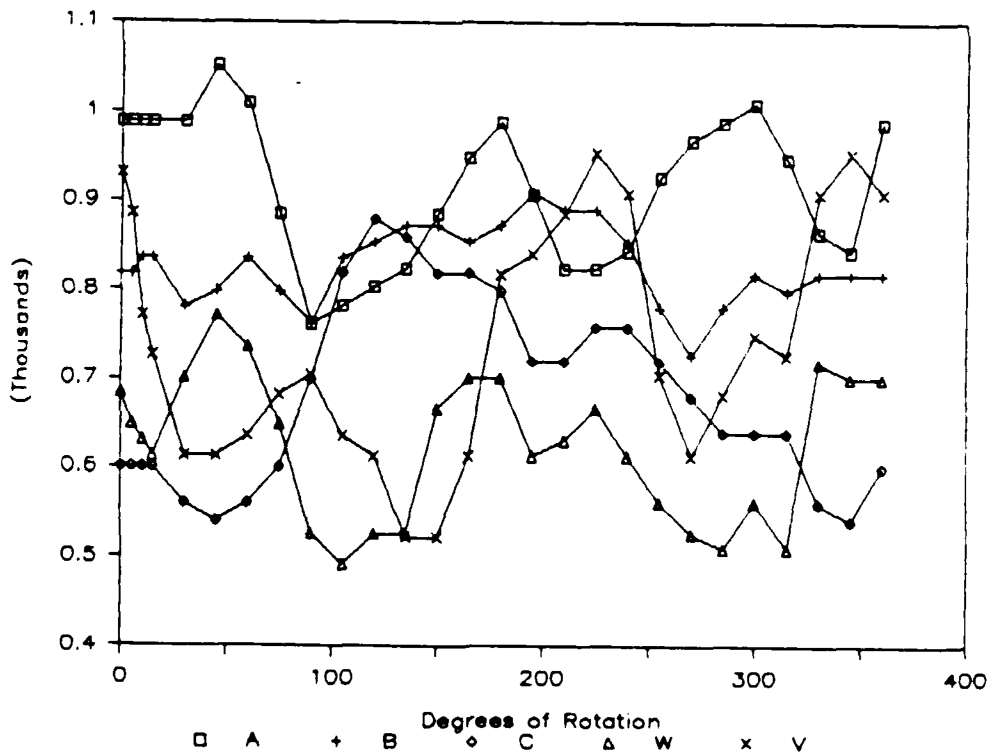


Figure 14. Correlation of 3 Exposure Filter (#3)

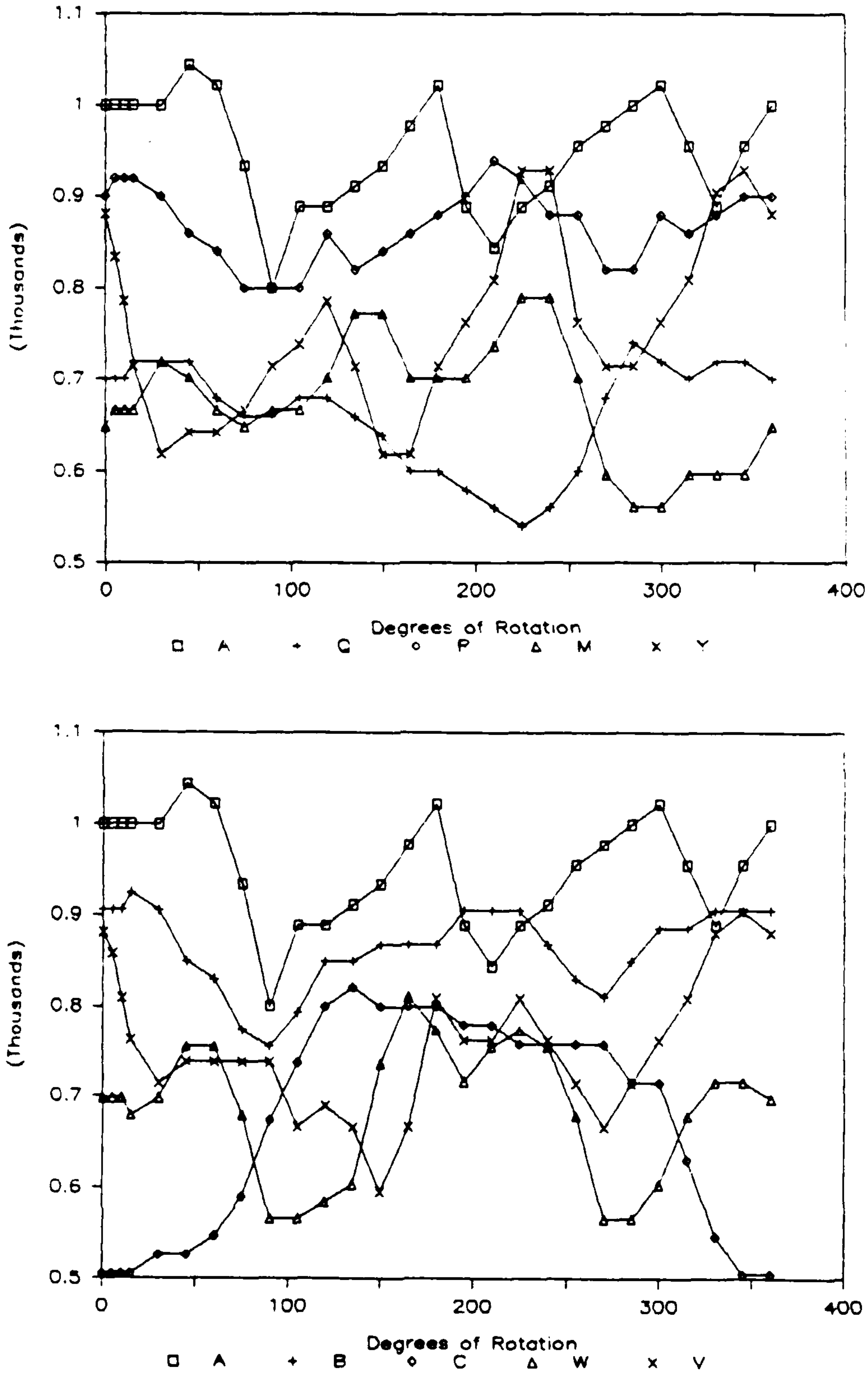
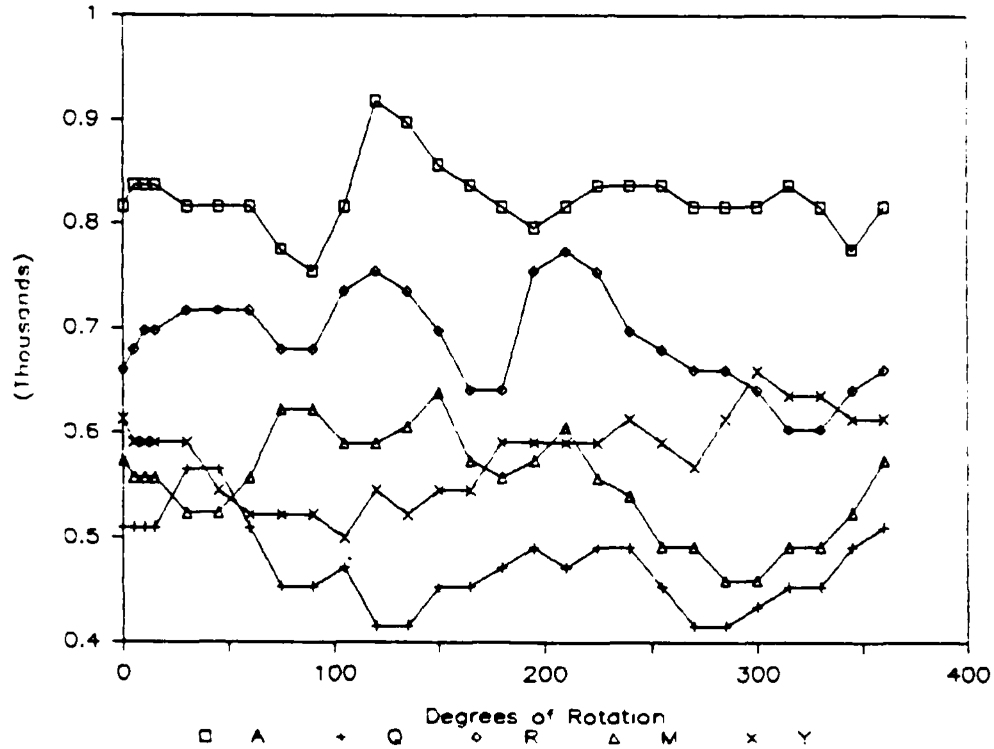


Figure 15. Correlation of 4 Exposure Filter (#4)



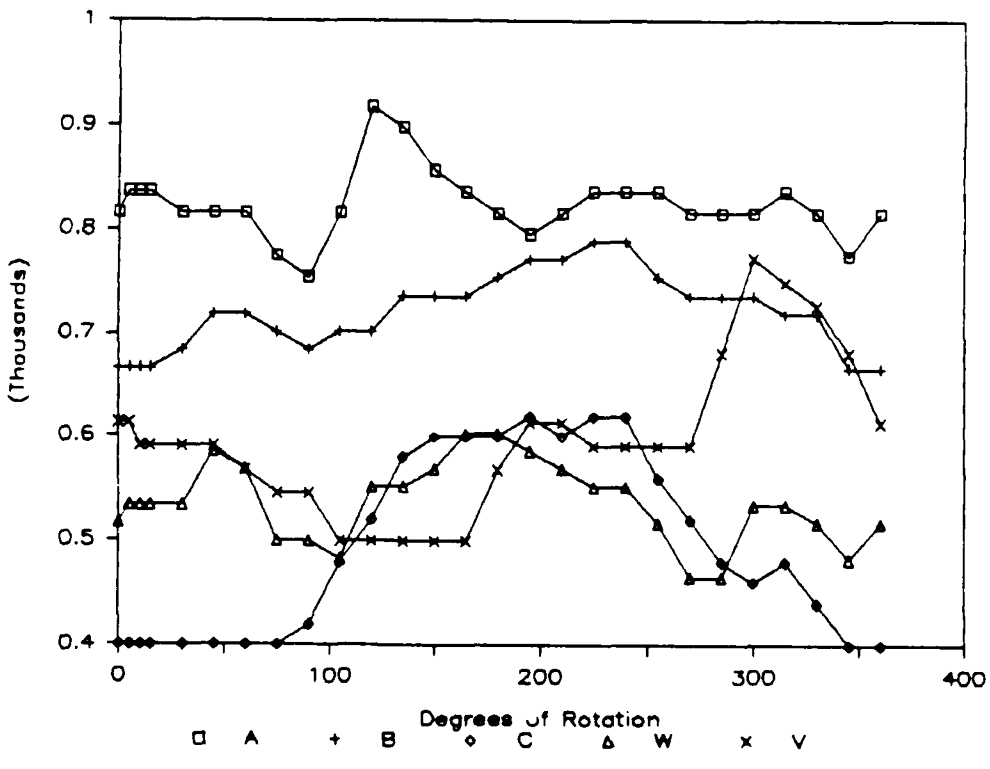


Figure 16. Correlation of 5 Exposure Filter (#5)

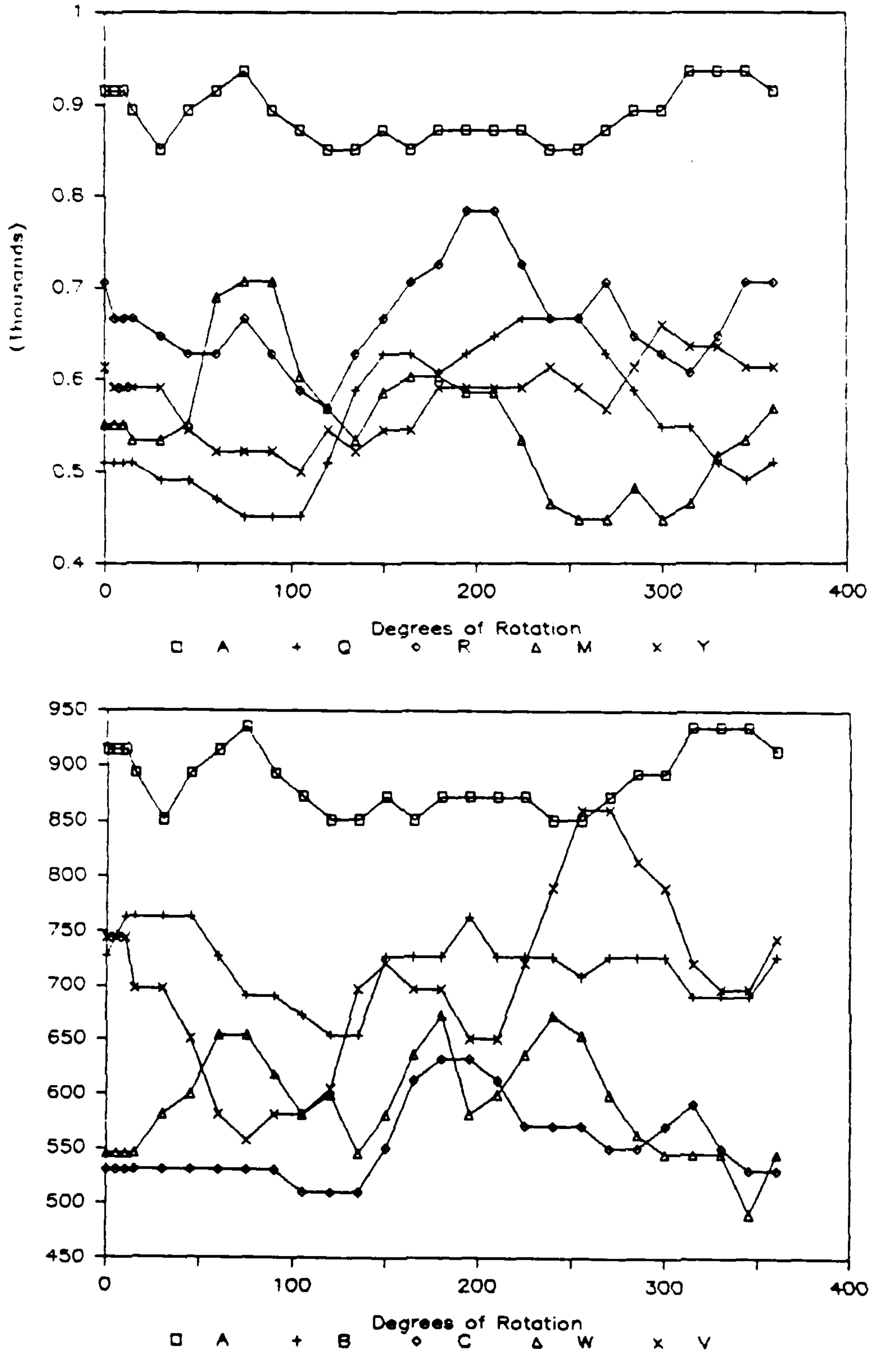


Figure 17. Correlation of 6 Exposure Filter (#6)

the same matched filter, the intra-class recognition should continue to increase. This can be considered to be a completely optical synthetic discriminant function. Figures 14-17 show how the addition of new rotational variations improves the intra-class recognition.

By looking at the previous correlation plot, the engineer can discern what rotation must be added to improve the operation of the next filter. Notice how the final filter (filter #6) shows excellent intra-class recognition while maintaining good inter-class discrimination.

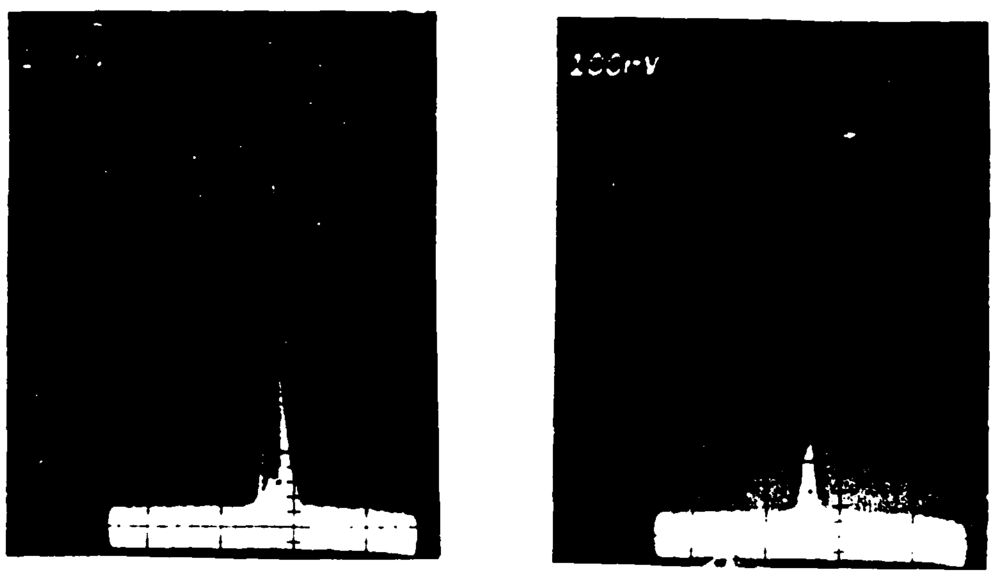


Figure 18. Correlation Spikes for Single Exposure (left) and Multiple Exposure (right)

Theoretically, the correlation should improve with each additional exposure. Unfortunately, this is

impractical. Each time a new rotational variation is added, the individual exposure times are decreased. Thus, each exposure moves the transmittance function down the H-D curve (Appendix A) reducing the correlation intensity. Eventually, the correlation spike is no longer discernable above the noise. Figure 18 shows the difference in the correlation spike between a single exposure filter and a multiple exposure filter. A good practical limit was found to be six exposures which provided a signal to noise ratio of approximately four decibels.

III.5. Spatial Filtering

The next experiment involved spatial filtering of the input. This study was designed to ascertain the ability of the matched filter to perform with a limited amount of information. In addition, the experiment showed what portions of the Fourier transform are most important for pattern recognition.

Using the set-up of Figure 5, spatial filters were placed in plane P_2 during both construction and testing of the matched filter. A small iris was used as the low-pass filter, and a dot placed on a glass plate served as the high-pass filter.

In the first portion of the experiment the filter used in sections III.2 and III.3 (filter #1) was placed in plane P_2'. The iris was placed in plane P_2 and adjusted so that

only the first four harmonics passed through the plane. Similarly, the iris was adjusted for three harmonics and for two harmonics. The results of the correlation measurements are shown in Figures 19-21. Notice that there is no appreciable difference between the regular matched filter correlation (Figure 9) and the spatially filtered correlation (Figure 21). Thus, we can conclude that the information necessary for matched filtering is contained in the first two harmonics of the Fourier transform (7)(8).

Next, a filter was constructed using only the first two harmonics. This filter was tested using the complete Fourier transform and also using only two harmonics. By comparing Figures 22 and 23 it can be seen once again that there is no appreciable change in the correlation when only the first two harmonics are used.

Filter #1 was returned to plane P_2'. The high-pass filter was placed in plane P_2 and adjusted to block out the DC term plus the first two harmonics. No measurable correlation was detected with this configuration. By examining Figure 24, it can be seen that nearly all of the energy contained in the Fourier transform of the letter "A" resides in the low harmonics. During the recording process the higher harmonics are at a very low point on the H-D curve (Appendix B); thus, the correlation was not detectable.

A new filter was constructed using a high-pass input.

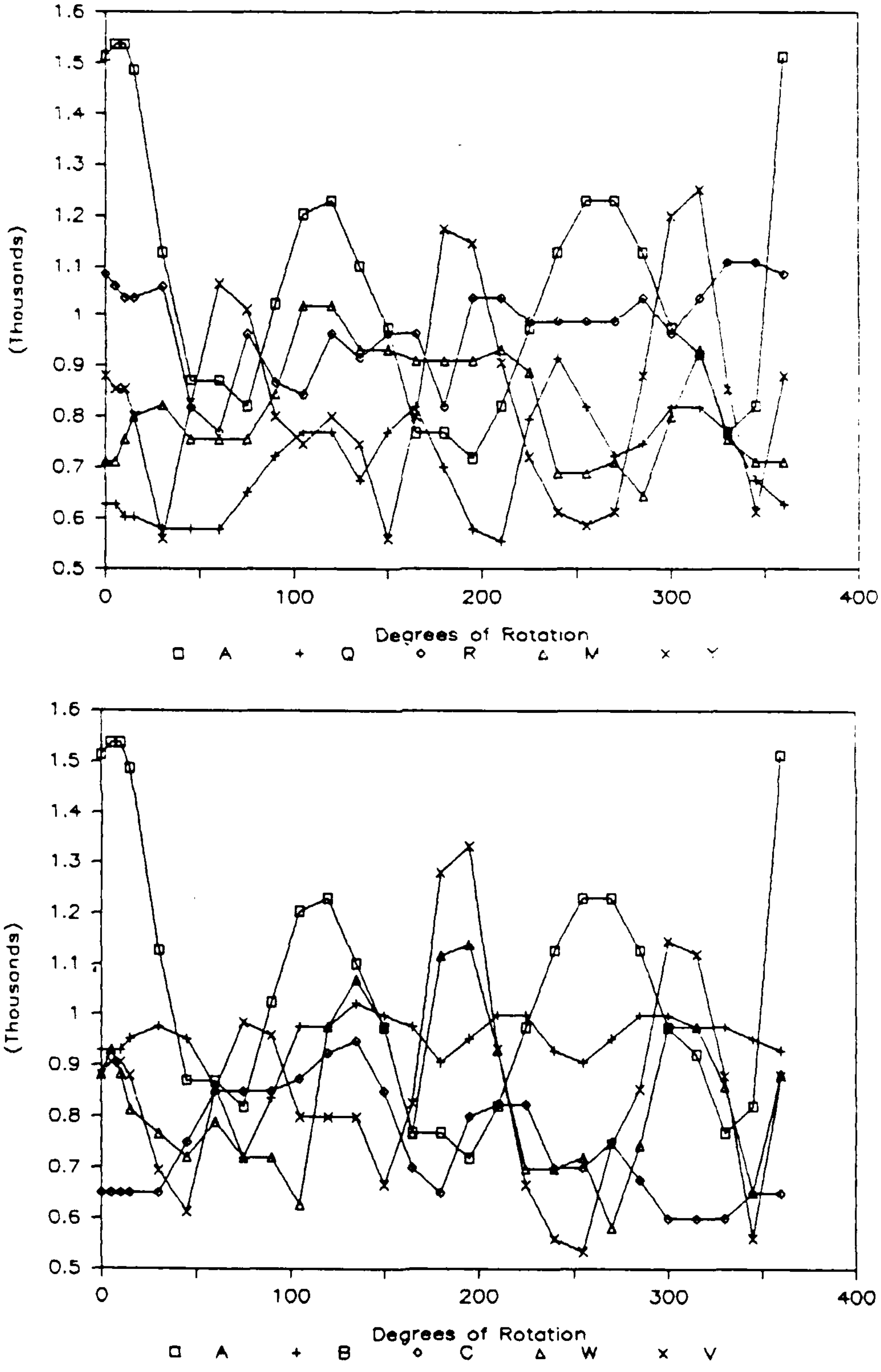


Figure 19. Filter #1 Correlation with 4 Harmonic Inputs

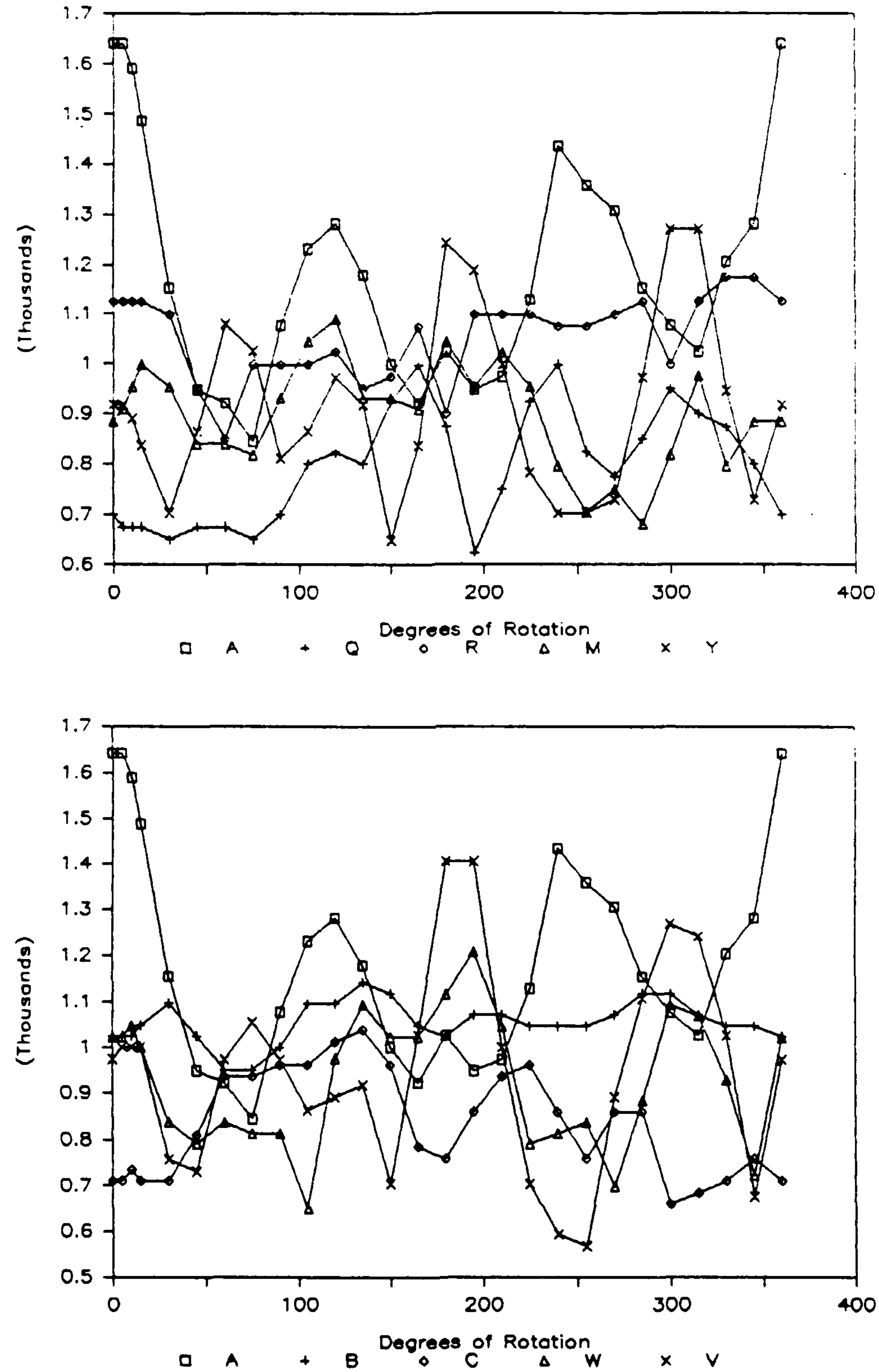


Figure 20. Filter #1 Correlation with 3 Harmonic Inputs

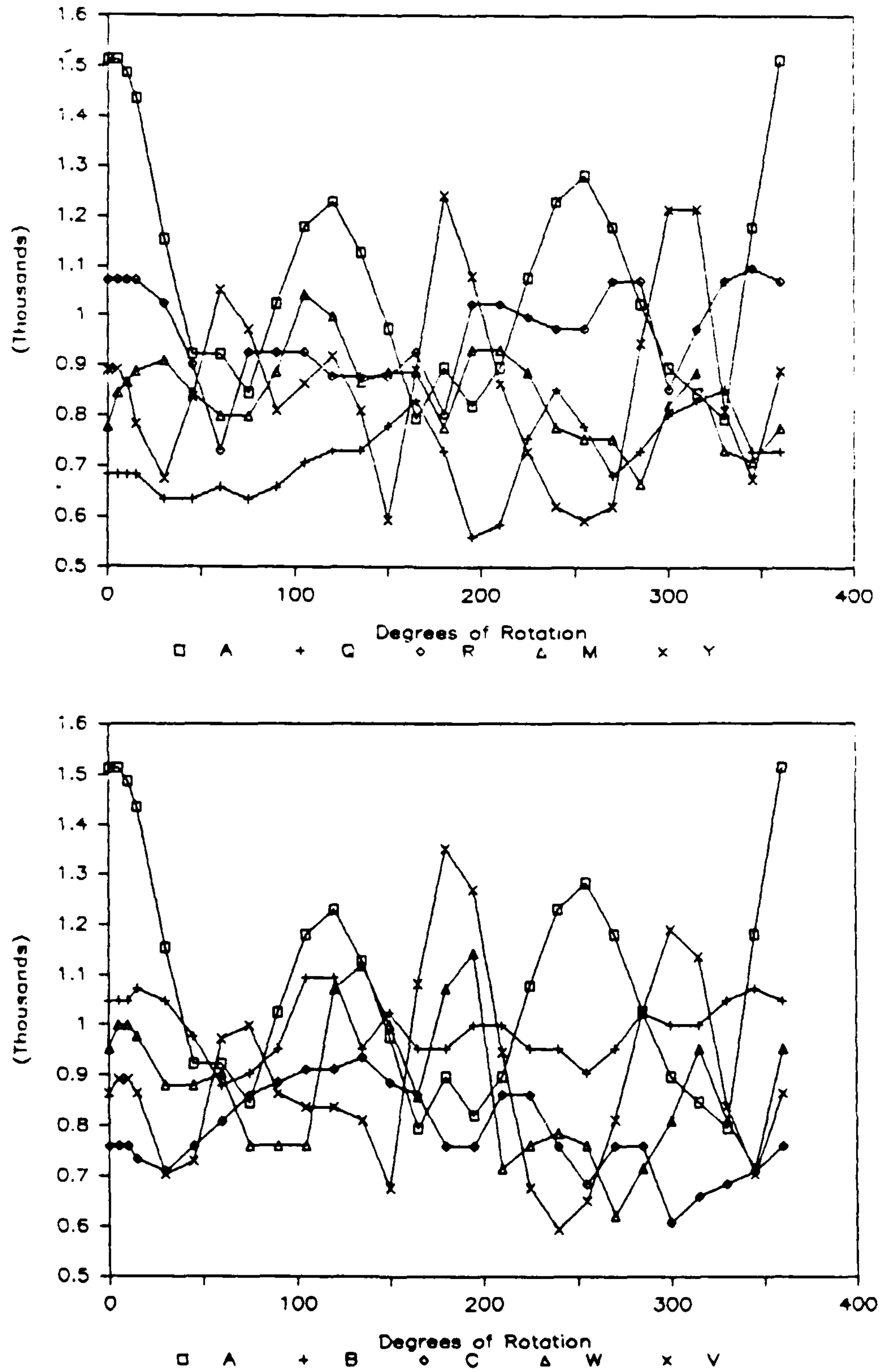
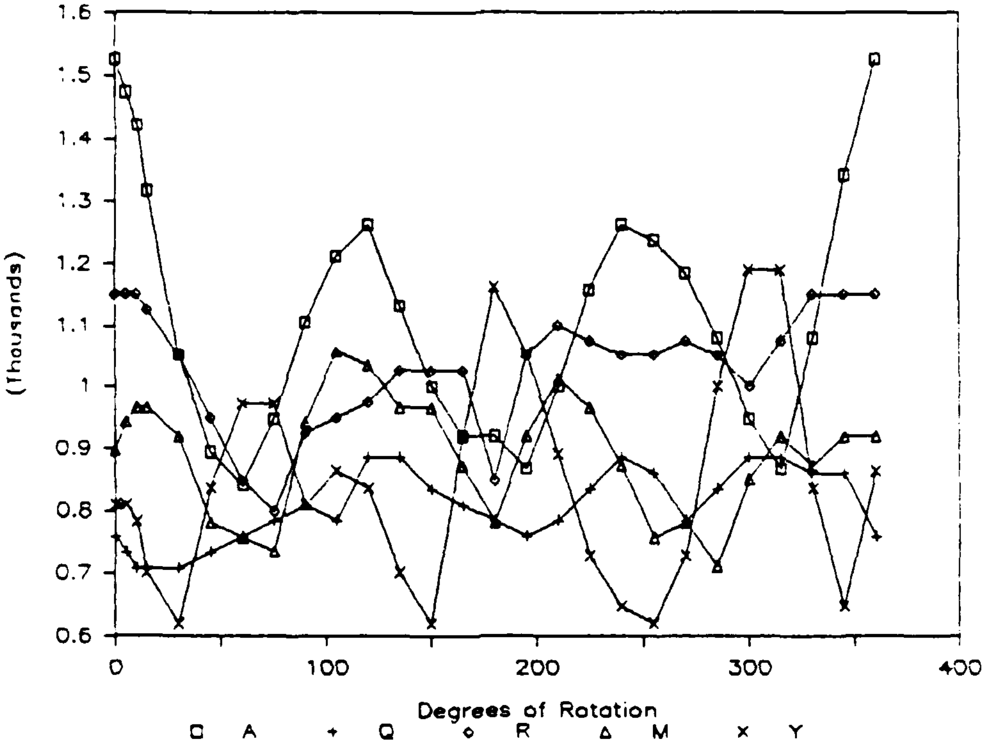


Figure 21. Filter #1 Correlation with 2 Harmonic Inputs



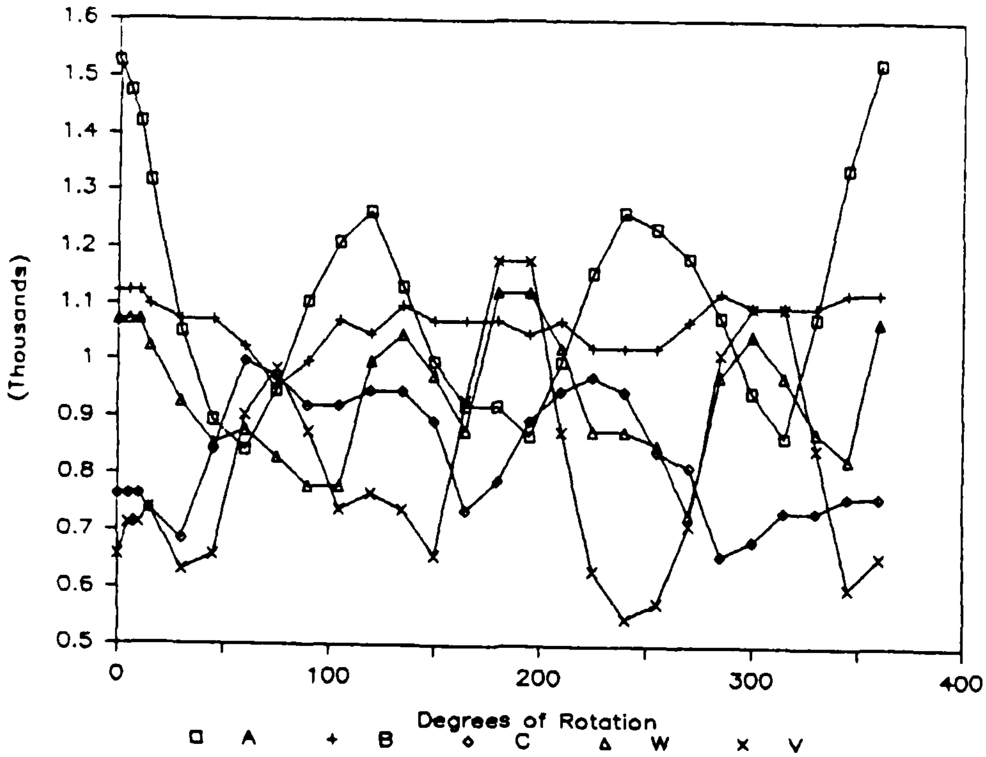
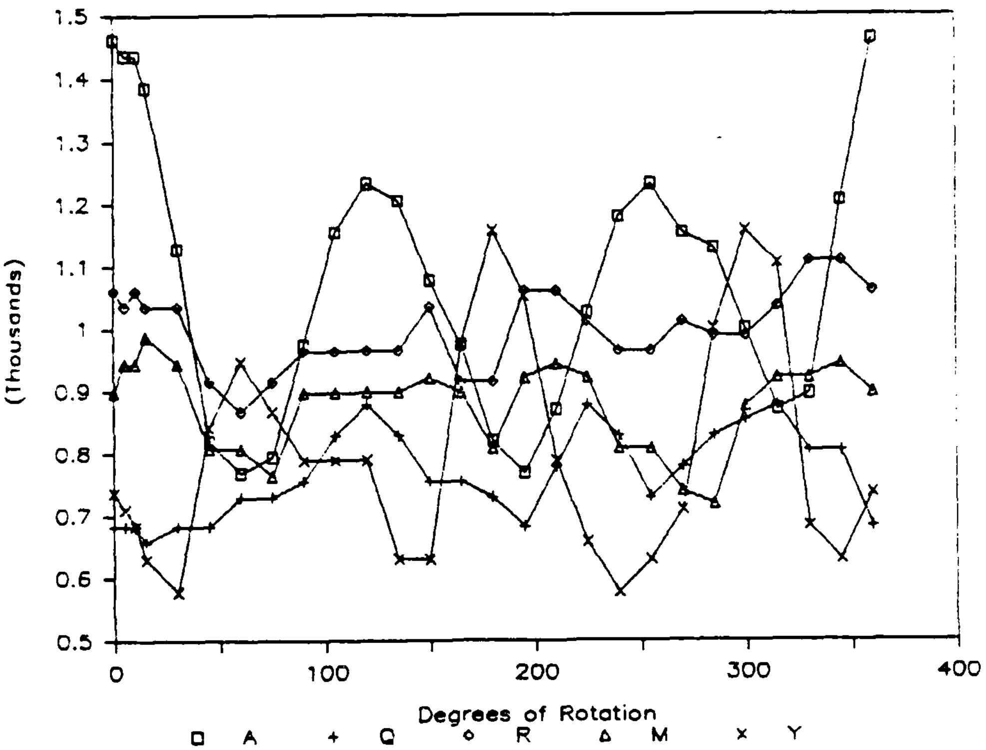


Figure 22. Low-pass Filter Correlation



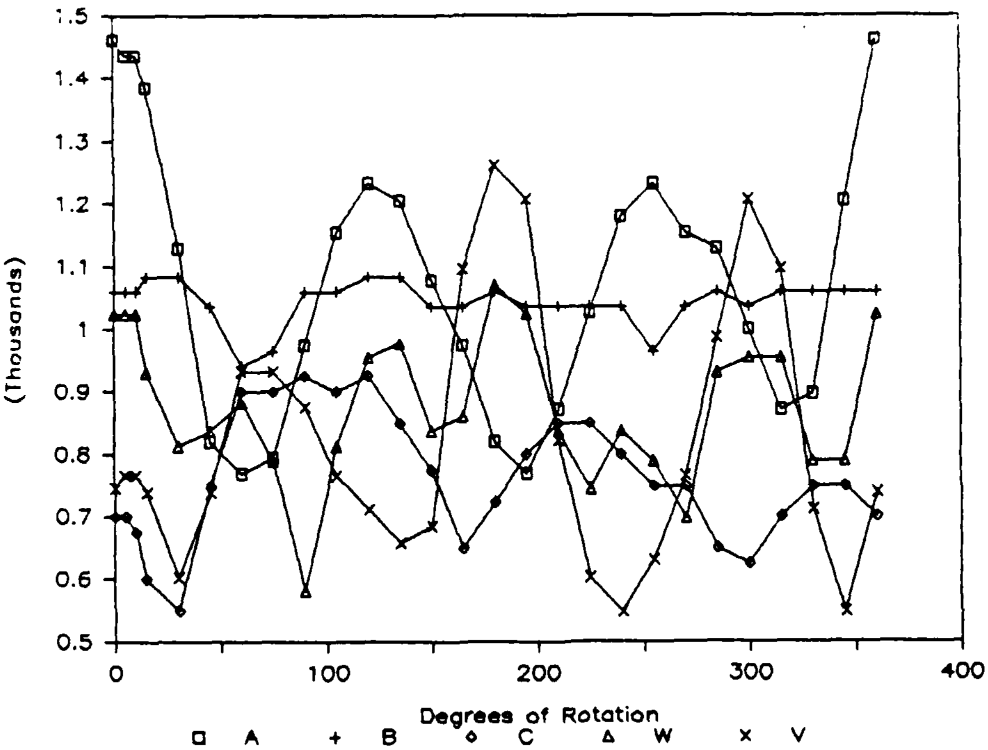


Figure 23. Low-pass Filter Correlation with

2 Harmonic Inputs

This time the higher harmonics were recorded in the linear region of the film. This filter was tested with the complete Fourier transform and also with a high-pass input. No appreciable correlation was detected for the complete input case since such a small portion of the input energy was contained in the higher harmonics. The correlation with the high pass input is shown in Figure 25. Note that this configuration offers excellent inter-class discrimination, but the intra-class recognition is very poor.

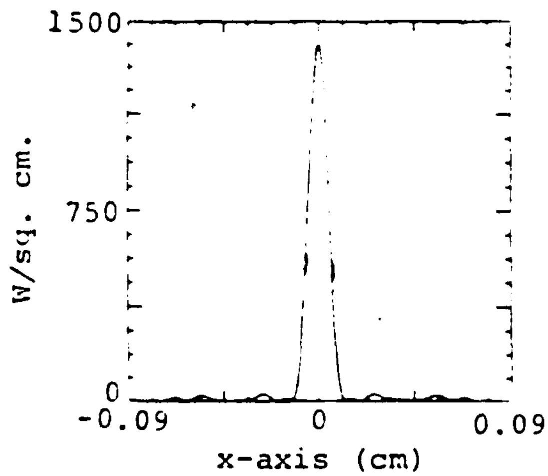


Figure 24. Energy in the Fourier Transform of "A"

III.6. Averaging

The next portion of this study involved averaging the correlation intensities. Using the values in section III.5, averages were taken of the correlation intensity over 360° of rotation. Figure 26 shows the average correlation of filter #1. When comparing this to the average correlation of filter #6 (Figure 27), it becomes apparent

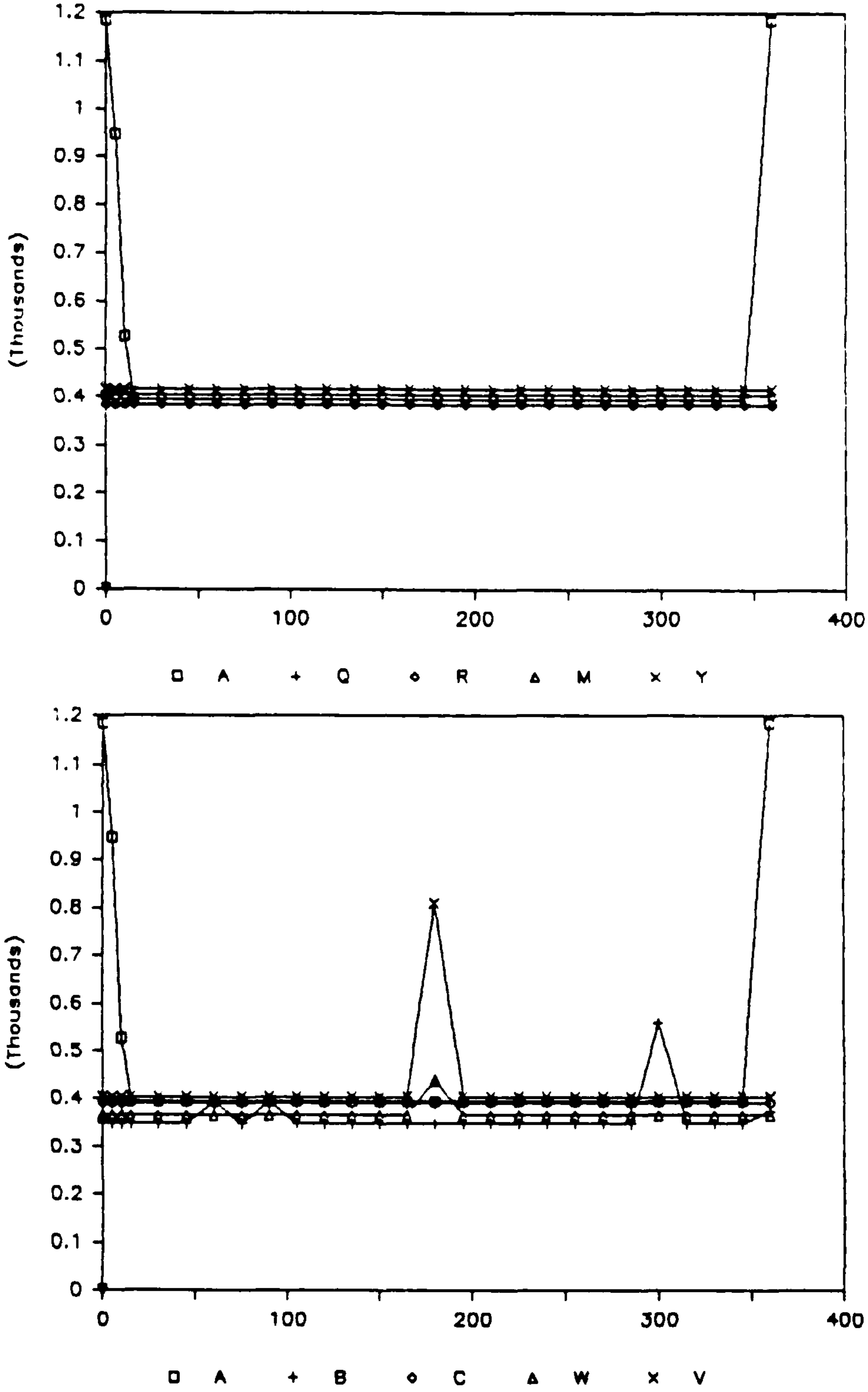


Figure 25. High-pass Filter Correlation with

High-pass Inputs

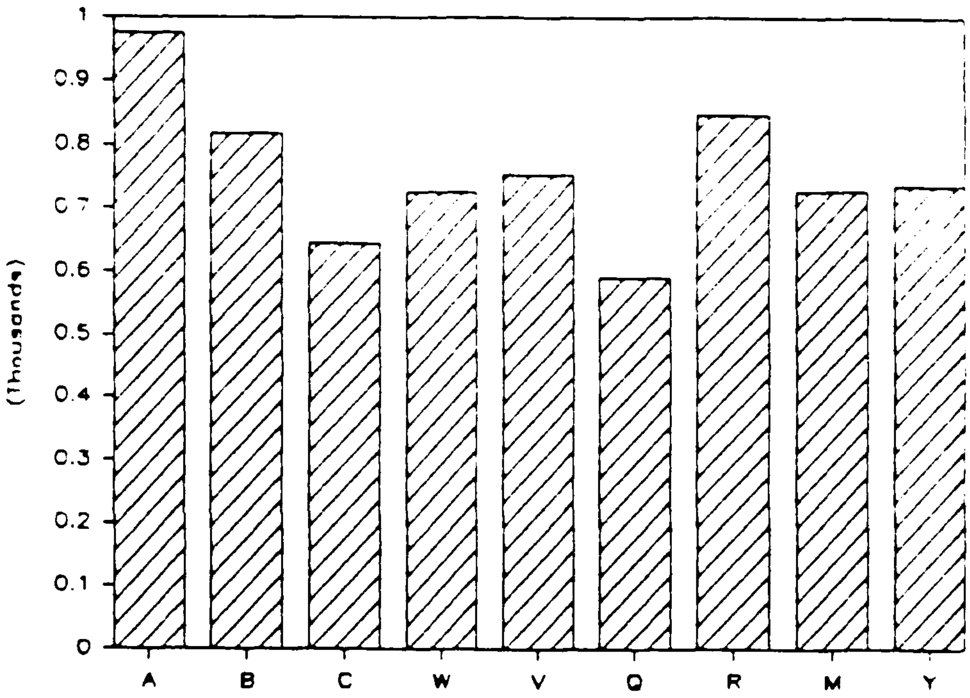


Figure 26. Average Correlation for Filter #1

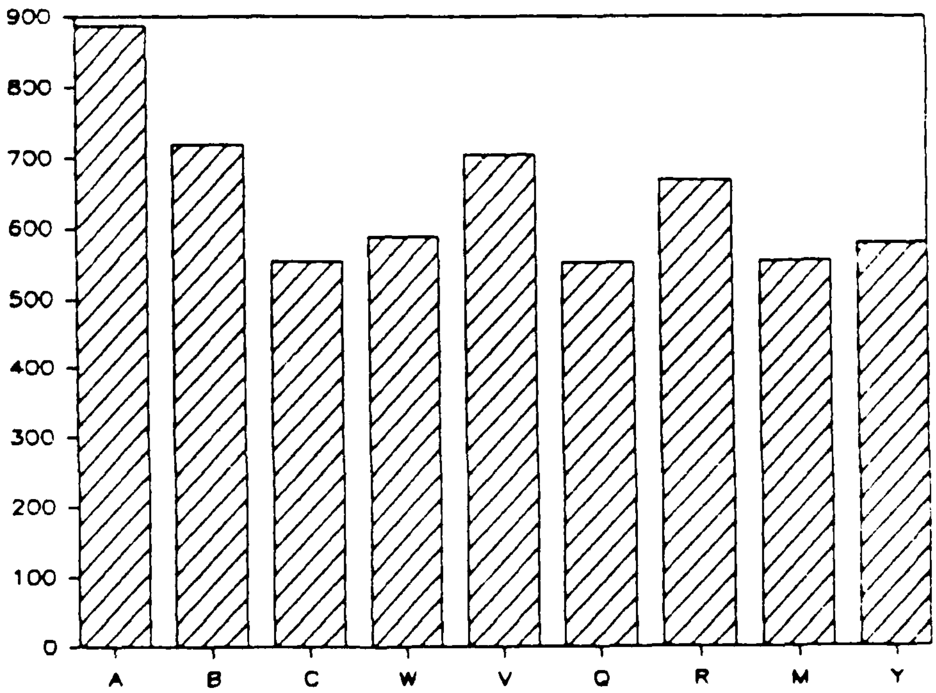


Figure 27. Average Correlation for Filter #6

that the multiple exposure technique has very little effect. Thus, averaging accomplishes both inter-class discrimination and intra-class recognition without having to make a synthetic discriminant function filter.

III.7. Correlation Variations with Input Movement

The final portion of this study involved looking at the effectiveness of the matched filter to operate as a tracking system. Theoretically, as the input is shifted in a direction parallel to plane P_1, the position of the correlation spike in plane P_3 will also shift in a corresponding manner. This effect was observed in the laboratory and confirmed the theory.

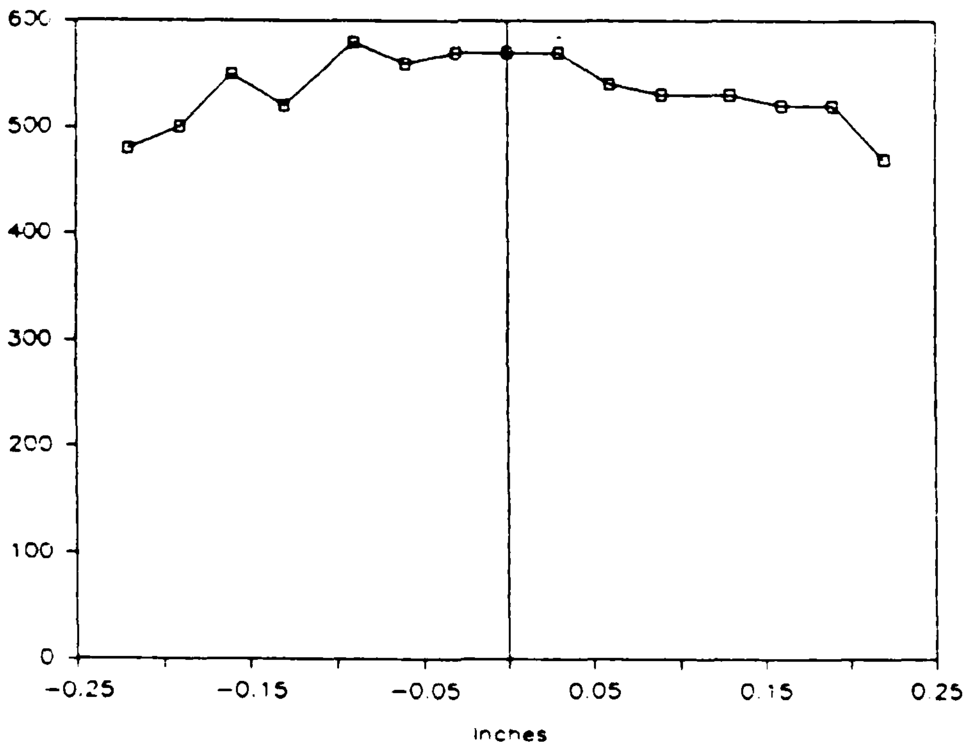


Figure 28. Correlation Intensity vs. Input Translation

Unfortunately, as the correlation spike moves, its intensity changes. Figure 28 shows the change in intensity as a function of input translation. Two other studies have noted similar results (1)(5). Brousseau and Arsenault attributed this problem to the finite aperture of the lenses and also to the thickness of the hologram (1).

The reduction in correlation intensity must be taken into account when setting a threshold value for the detector in a practical system. As the threshold is lowered, the discrimination capabilities are effectively reduced.

III.8. Special Considerations

Several factors must be considered when choosing a matched spatial filter system for optical pattern recognition. The first factor is that of time. Constructing a matched filter takes several hours. After setting up the system, the engineer must expose the holographic plate, develop it, and then allow the emulsion to dry for approximately four hours. Then, the filter must be tested for efficiency and discrimination capabilities.

The reason for testing the filter is that the construction process has a large number of variables. Factors such as beam ratio, laser power, exposure time, and development time must be accurately controlled to ensure repeatability. Deviations in any one of these factors can cause the effectiveness of the filter to be reduced.

The most important factor to be considered is the rigidity of the surroundings. Many of the optics in the system are in critical alignment. The slightest bump could cause the processor to completely lose correlation. The amount of correlation degradation was discussed in Chapter II for the case of matched filter translation. Moving a lens just a few microns can cause similar problems.

Thus, all of these factors must be weighed when considering the use of matched spatial filters.

Chapter IV

IV.1. Conclusions

This thesis describes the usefulness of the matched spatial filter in an optical pattern recognition system. Several drawbacks of the filter were discussed and techniques were proposed to solve some of these problems.

The regular matched filter constructed using the Vander Lugt technique (17) showed an excellent capability for inter-class discrimination. Energy normalization was added to make the discrimination even better. The regular filter also showed poor intra-class recognition when applied to rotational variations of the object.

An iterative method that produces optical synthetic discriminant functions was introduced. This method provided a means for constructing matched filters capable of inter-class discrimination as well as intra-class recognition.

Spatial filtering was examined as a possible means for increasing the efficiency of matched filters. High-pass filters provided excellent inter-class discrimination, but its intra-class recognition was extremely poor. Low-pass filters had very little affect on correlation showing that most of the information necessary for pattern recognition was contained in the first two harmonics. Thus, for syn-

thetic discriminant function applications spatial filtering is of little use.

Averaging was applied to the correlation outputs to boost the discrimination capabilities of the matched filter. It was found that averaging provided good inter-class discrimination and intra-class recognition without making use of multiple exposure holograms.

Through the techniques of energy normalization, multiple exposure holograms, and correlation averaging, the efficiency of the matched spatial filter was increased. This thesis shows that the matched filter can be used effectively in a pattern recogniton system.

IV.2. Recommendations

Several areas of optical pattern recognition still need to be investigated to make the system more practical. First, a method of optical energy normalization must be developed for the case of multiple targets. Since the energy normalization used in this thesis assumed only one target in the field of view, the procedure needs to be expanded to include the multiple target case. This will make full use of the matched filter's capabilities.

A second area of research includes correlation in a noisy background. Once again this is a problem of energy normalization.

A third problem, which has been drawing much attention

lately, is real-time correlation. Using spatial light modulators in the input or Fourier transform plane can add a tremendous amount of flexibility to the process.

Appendix A

Holographic Film Characteristics

The construction of matched spatial filters greatly depends upon the use of holographic film. Therefore, an understanding of basic film theory is necessary to fully grasp the concept of matched filter construction.

Photographic film consists of two parts, the base and the emulsion. The base is usually an acetate film or a glass plate. Its function is to provide a stable support for the active medium (emulsion). The emulsion consists of a large number of tiny silver halide particles suspended in a gelatin. These particles are photosensitive and undergo a physical change when exposed to light. The silver halide particles that absorb enough energy are reduced into tiny metallic silver particles called development centers.

The film then undergoes a chemical process during which the silver halide particles containing development centers are reduced entirely to metallic silver. Finally, the film is "fixed". During this process the unexposed silver halide grains are removed leaving only the exposed silver particles suspended in the gelatin. These particles are opaque at optical frequencies. The density of the silver halide grains in the gelatin affects the resolution of the film; therefore, it also affects the transmittance of the film. Since interference fringes are very fine, a very

high resolution film must be used when making matched spatial filters.

Most film is characterized by its H-D (Hurter-Driffield) curve (Figure A1)(19:103). The plot shows the density of the developed silver grains versus the logarithm of the exposure. (Exposure is defined as the energy per unit area incident at each point on the photosensitive surface (9:150).) The H-D curve contains three major regions. The first region is that below the toe or the gross fog region. In this area the density is independent of the exposure level. Another non-linear region occurs at the other end of the curve when the film saturates. The major region of interest is the linear region where an increase in exposure triggers a linear increase in density.

The slope of the curve in this region is referred to as the film gamma, . Film with a large value of is referred to as high-contrast film; whereas, a low gives rise to low-contrast film (19:104).

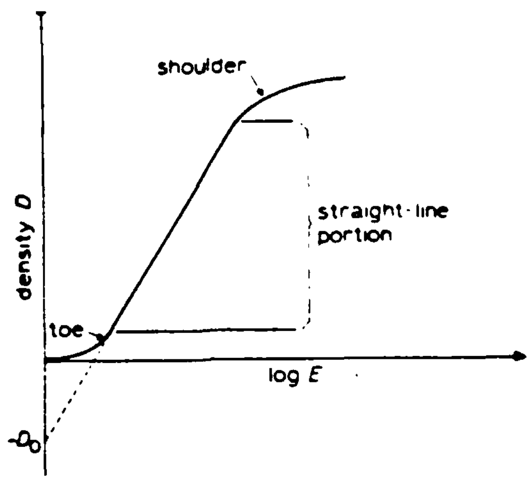


Figure A1. Hurter Driffield Curve (19:104)

The intensity transmittance of the developed transparency is defined to be:

$$\tau(x,y) = \text{ensemble average} \left[\frac{I[\text{transmitted } \epsilon (x,y)]}{I[\text{incident } \epsilon (x,y)]}\right] \tag{A1}$$

Similarly, the photographic density is defined as:

$$D = \log \left[\frac{1}{\tau}\right] \tag{A2}$$

If the film is recorded in the linear region then we have

$$D = \gamma \log E - D_0 \tag{A3}$$

Substituting (A2) into (A3) we find that

$$\log\tau = -\gamma \log(It) + D_0 \tag{A4}$$

where I=incident intensity and t=exposure time. Thus, we have

$$\tau = K\, I^{-\gamma} \tag{A5}$$

where $K = 10^{D_0} t^{-\gamma}$

Obviously, the transmittance is not linear with respect to incident intensity. Note also that as the intensity increases the transmittance decreases.

We can also define an amplitude transmittance to be

$$T(x,y) = \sqrt{\tau(x,y)}\, \exp(j\phi(x,y)) \tag{A6}$$

where $\phi(x,y)$ accounts for phase shifts introduced by variations in the thickness of the base. By using a glass plate instead of acetate film, these phase shifts can be minimized.

Appendix B

Hologram Developing Process

Kodak 649-F Spectroscopic Plates were used throughout this thesis to construct the matched filters. After the plate was exposed, it was developed using the process shown below.

1. Place the plate in developer (D-19) for 5 minutes.

2. Remove the plate from the developer and place it in stopper for 30 seconds.

3. Remove the plate from the stopper and place it in fixer (Rapid fix) for 5 minutes.

4. Remove the plate from the fixer and wash it in distilled water for 10-30 minutes.

5. Allow the plate to dry for at least 4 hours.

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This thesis analyzes the applicability of the matched spatial filter to optical pattern recognition when the object has been rotated relative to the filter. Several techniques are introduced to enhance the discrimination efficiency of the matched filter.

Energy normalization was applied to compensate for the variance in the reflected energy of targets. This allowed the matched filter to detect the desired target in the presence of bright background noise. A rotation invariant matched filter was constructed using multiple exposure holograms. Correlation averaging was also applied to make the filter rotation invariant.

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